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# canadian acoustics
# acoustique canadienne

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# canadian acoustics

**Canadian Acoustical Association/Association Canadienne d'Acoustique P.B. 74068 Ottawa, Ontario, K1M 2H9**

Canadian Acoustics publishes refereed articles and news items on all aspects of acoustics and vibration. Articles reporting new research or applications, as well as review or tutorial papers and shorter technical notes are welcomed, in English or in French. Submissions should be sent only through the journal online submission system. Complete instructions to authors concerning the required "camera-ready" manuscript are provided within the journal online submission system.

Canadian Acoustics is published four times a year - in March, June, September and December. This quarterly journal is free to individual members of the Canadian Acoustical Association (CAA) and institutional subscribers. Canadian Acoustics publishes refereed articles and news items on all aspects of acoustics and vibration. It also includes information on research, reviews, news, employment, new products, activities, discussions, etc. Papers reporting new results and applications, as well as review or tutorial papers and shorter research notes are welcomed, in English or in French.The Canadian Acoustical Association selected Paypal as its preferred system for the online payment of your subscription fees. Paypal supports a wide range of payment methods (Visa, Mastercard, Amex, Bank account, etc.) and does not requires you to have already an account with them. If you still want to proceed with a manual payment of your subscription fee, please use the application form from the CAA website and send it along with your cheque or money order to the secretary of the Association (see address above). - Canadian Acoustical Association/Association Canadienne d'Acoustiquec/o JASCO Applied Sciences2305–4464 Markham StreetVictoria, BC V8Z 7X8 Canada - - - secretary@caa-aca.ca - Dr. Roberto Racca

# acoustique canadienne

**Association canadienne d'acoustique B.P. 74068 Ottawa, Ontario, K1M 2H9**

L'Acoustique Canadienne publie des articles arbitrés et des informations sur tous les aspects de l'acoustique et des vibrations. Les informations portent sur la recherche, les ouvrages sous forme de revues, les nouvelles, l'emploi, les nouveaux produits, les activités, etc. Des articles concernant des résultats inédits ou des applications ainsi que les articles de synthèse ou d'initiation, en français ou en anglais, sont les bienvenus.

Acoustique canadienne est publié quantre fois par an, en mars, juin, septembre et décembre. Cette revue trimestrielle est envoyée gratuitement aux membres individuels de l'Association canadienne d'acoustique (ACA) et aux abonnés institutionnels. L'Acoustique canadienne publie des articles arbitrés et des rubriques sur tous les aspects de l'acoustique et des vibrations. Ceci comprend la recherche, les recensions des travaux, les nouvelles, les offres d'emploi, les nouveaux produits, les activités, etc. Les articles concernant les résultats inédits ou les applications de l'acoustique ainsi que les articles de synthèse, les tutoriels et les exposées techniques, en français ou en anglais, sont les bienvenus.L'Association canadienne d'acoustique a sélectionné Paypal comme solution pratique pour le paiement en ligne de vos frais d'abonnement. Paypal prend en charge un large éventail de méthodes de paiement (Visa, Mastercard, Amex, compte bancaire, etc) et ne nécessite pas que vous ayez déjà un compte avec eux. Si vous désirez procéder à un paiement par chèque de votre abonnement, merci d'utiliser le formulaire d'adhésion du site de l'ACA et de retourner ce dernier avec votre chèque ou mandat au secrétaire de l'association (voir adresse ci-dessus). - Canadian Acoustical Association/Association Canadienne d'Acoustiquec/o JASCO Applied Sciences2305–4464 Markham StreetVictoria, BC V8Z 7X8 Canada - - - secretary@caa-aca.ca - Dr. Roberto Racca

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# WELCOME TO GUELPH !

## ACOUSTICS WEEK IN CANADA 2017

## OCTOBER 11 – 13, 2017

## Organizing Committee

| | |
|---|---|
| Conference Chair: | Peter VanDelden, RWDI |
| Technical Chair: | Christian Giguère, University of Ottawa |
| Exhibit and Sponsorship: | Bernard Feder, HGC Engineering |
| Registration and Treasurer: | Dalila Giusti, Jade Acoustics |
| Conference Website: | Kyle Hellewell, RWDI |
| Proceedings Preparation: | Cécile Le Cocq, Université du Québec (ÉTS) |
| | Olivier Valentin, Université du Québec (ÉTS) |

Conference Website: **http://awc.caa-aca.ca**

# BIENVENUE À GUELPH !

## SEMAINE CANADIENNE DE L'ACOUSTIQUE 2017

## 11 – 13 OCTOBRE, 2017

## Comité organisateur

| | |
|---|---|
| Président de la conférence: | Peter VanDelden, RWDI |
| Président technique: | Christian Giguère, Université d'Ottawa |
| Expositions et commandites: | Bernard Feder, HGC Engineering |
| Inscription et trésorier: | Dalila Giusti, Jade Acoustics |
| Website de la conférence: | Kyle Hellewell, RWDI |
| Préparation des actes: | Cécile Le Cocq, Université du Québec (ÉTS) |
| | Olivier Valentin, Université du Québec (ÉTS) |

Website de la conférence: **http://awc.caa-aca.ca**

# Guest Editorial
# Éditorial Invité

The small steps of a young child and the big steps of its parent both carry them forward towards a goal. In the same way, the Journal documents larger and smaller advances in the world of acoustics with longer and shorter papers. With this issue of the Journal we take a break from lengthier articles to present two-page summaries of conference presentations at Acoustics Week in Canada 2017.

Over 100 contributed talks form the backbone of the conference. This year the practice areas of the local acoustic community are strongly represented. The large proportion of talks in Architectural Acoustics, Environmental Noise and related fields are uncommon in the history of the conference. The contributed talks are headed by keynote speakers in the areas of hearing conservation, architectural acoustics and aeroacoustics. The National Research Council of Canada is also presenting a workshop that brings together years of Architectural Acoustics research in Sound Transmission. Details of the keynotes and workshop are found on the following pages.

The conference is generously supported by community-minded sponsors. In recognition of their contributions, the corporate logos are included in the subsequent pages. Once again this year we offer an exhibition of products and services relating to the field of acoustics. Approximately 30 companies and organizations are represented! We thank them for their participation. Please support these companies.

The host city for Acoustics Week in Canada 2017 is Guelph, Ontario. The city is 190 years old, but has a vibrant central core and the feeling of a smaller community. Guelph is home to the birthplace of John McCrae, author of the poem "In Flanders' Fields". The Guelph Civic Museum is the starting point for exploration of the area's history. For those interested in festivals, the conference takes place in the middle of Oktoberfest. This celebration of German heritage takes place in Kitchener-Waterloo, approximately 40 minutes west of Guelph.

Enjoy the conference!
Peter VanDelden

Les petits pas d'un jeune enfant et les grandes enjambées de ses parents les portent tous deux vers un même but. De même manière, notre revue véhicule les grands et petits avancements dans le monde de l'acoustique par des articles de différentes ampleurs. Dans cette parution de la revue, nous prenons une pause d'articles plus longs pour présenter les sommaires de deux pages des présentations offertes à la Semaine canadienne de l'acoustique 2017.

Plus de 100 présentations scientifiques constituent l'épine dorsale du congrès. Cette année, les domaines de pratique de la communauté acoustique locale sont fortement représentés. Une telle proportion de présentations en acoustique architecturale, bruit environnemental et domaines connexes est très rare dans l'histoire du congrès. Ces présentations sont encadrées par celles de conférenciers-invités chevronnés dans les domaines de la préservation de l'ouïe, de l'acoustique architecturale et de l'aéroacoustique. Le Conseil national de recherches du Canada présente également un atelier qui rassemble des années de recherche en acoustique architecturale dans le domaine de la transmission du son. Vous trouverez plus de renseignements sur ces conférences invités et l'atélier dans les pages suivantes.

Le congrès est généreusement soutenu financièrement par nos partenaires du secteur privé. En reconnaissance de leurs contributions, les logos d'entreprise sont inclus dans les pages suivantes. Une fois de plus cette année, nous proposons une exposition de produits et services liés au domaine de l'acoustique. Environ 30 entreprises et organisations sont représentées! Nous les remercions de leur participation. Veuillez encourager ces entreprises.

La ville hôte de la Semaine canadienne de l'acoustique 2017 est Guelph, en Ontario. La ville a 190 ans et possède un centre dynamique mais reflétant une communauté plus petite. Guelph est le lieu de naissance de John McCrae, auteur du poème "In Flanders 'Fields". Le musée civique de Guelph est le point de départ de l'exploration de l'histoire de la région. Pour ceux qui s'intéressent aux festivals, le congrès se déroule en plein milieu de l'Oktoberfest. Cette célébration du patrimoine allemand a lieu à chaque année à Kitchener-Waterloo, à environ 40 minutes à l'ouest de Guelph.

Profitez bien du congrès!
Peter VanDelden

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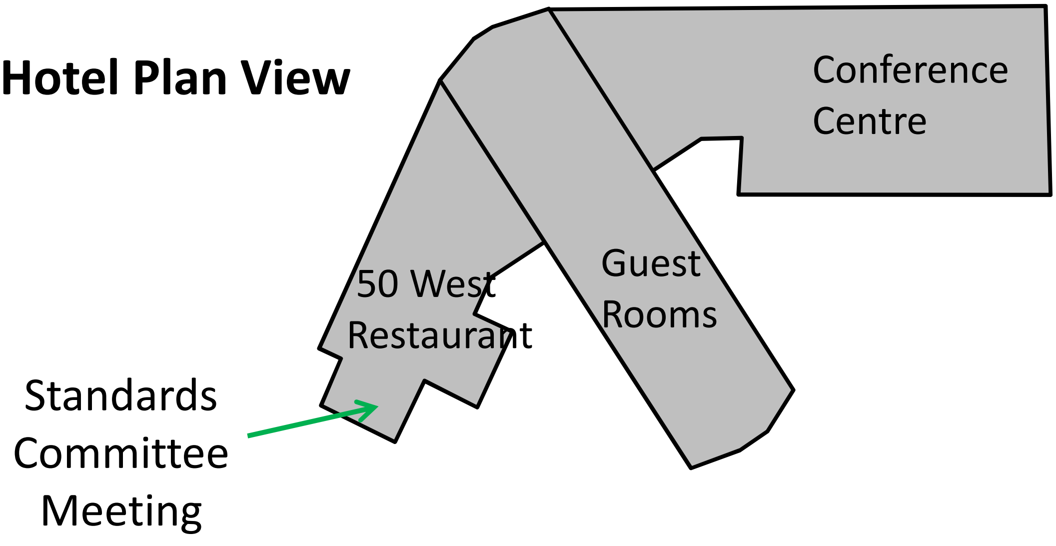
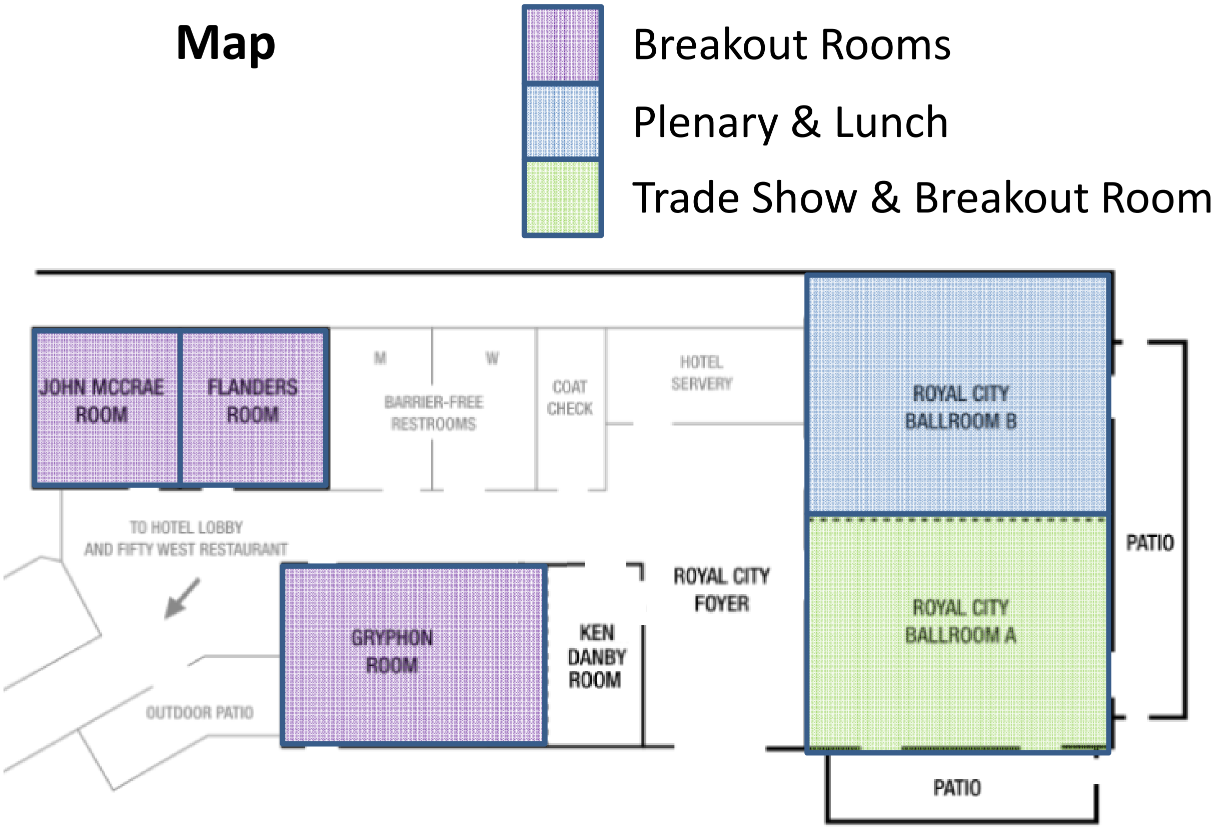
| **DAY ONE** | **WEDNESDAY 11 October 2017**<br>**Registration Opens at 8:00, Royal City Foyer** | | | |
|---|---|---|---|---|
| 8:50–9:00 | **WELCOME** | | | |
| 9:00–10:00 | **Plenary: Elliott BERGER (Royal City Ballroom B)**<br>***Bang! Damage from impulse noise and the effectiveness of hearing protection*** | | | |
| 10:00–10:20 | **COFFEE BREAK (Hallway)** | | | |
| | Gryphon Room | Flanders Room | John McCrae Room | Ballroom A |
| 10:20–12:20 | *Occupational Noise and Standards I* | *Environmental Noise Assessment* | *Architectural Acoustics Modelling* | *Architectural Acoustics Applications I* |
| 12:20–1:20 | **LUNCH (Royal City Ballroom B)** | | | |
| 1:20–3:20 | *Occupational Noise and Standards II*<br>*Green Building Acoustics* | *Shock and Vibration* | *Education in Acoustics I* | |
| 3:20–3:40 | **COFFEE BREAK (Hallway)** | | | |
| 3:40–5:20 | *Architectural Sound Transmission I* | *Wind Turbines* | *Education in Acoustics II* | |
| 5:30–7:00 | **Tours** | | | |
| 7:00-8:30 | **WELCOME RECEPTION & EXHIBITOR SHOW OPENING**<br>**(Royal City Ballroom A-B)** | | | |
| | | | | |
| **DAY TWO** | **THURSDAY 12 October 2017** | | | |
| 8:35-8:40 | **OPENING REMARKS** | | | |
| 8:40–9:40 | **Plenary: John BRADLEY (Royal City Ballroom B)**<br>***A Rationale for a National Classroom Acoustics Standard*** | | | |
| 9:00–17:00 | ***EXHIBITION (Royal City Ballroom A)*** | | | |
| 9:40–10:20 | **COFFEE BREAK (Royal City Ballroom A)** | | | |
| | Gryphon Room | Flanders Room | John McCrae Room | Ballroom A |
| 10:20–12:00 | *NRC Workshop* | *Hearing Sciences I* | | *exhibition* |
| 12:00–1:00 | **LUNCH (Royal City Ballroom B)** | | | |
| 1:00–3:00 | *NRC Workshop* | *Hearing Sciences II*<br>*Biomedical Acoustics and Ultrasounds* | | *exhibition* |
| 3:00–3:40 | **COFFEE BREAK** | | | |
| 3:40–5:00 | *Architectural Sound Transmission II* | *Speech Sciences* | *Environmental Noise Modelling* | |
| 5:15–6:15 | **CAA ANNUAL GENERAL MEETING (ROOM: Gryphon Room)** | | | |
| 6:15–9:30 | **AWC 2017 BANQUET & AWARDS** | | | |
| | | | | |
| **DAY THREE** | **FRIDAY 13 October 2017** | | | |
| 8:35-8:40 | **OPENING REMARKS** | | | |
| 8:40–9:40 | **Plenary: Samir ZIADA (Royal City Ballroom B)**<br>***Flow-excited Acoustic Resonances in Small Cavities*** | | | |
| 9:40–10:00 | **COFFEE BREAK (Hallway)** | | | |
| | Gryphon Room | Flanders Room | John McCrae Room | Ballroom A |
| 10:00–12:20 | *Speech Communication* | *Aeroacoustics* | *Environmental Noise Criteria* | *Architectural Acoustics Applications II* |
| 12:20–1:40 | **LUNCH & STUDENT PRESENTATION AWARDS (Royal City Ballroom B)** | | | |

## Hotel Plan View



## Conference Centre Map



# Plenary Speakers
# Conférences Plénières

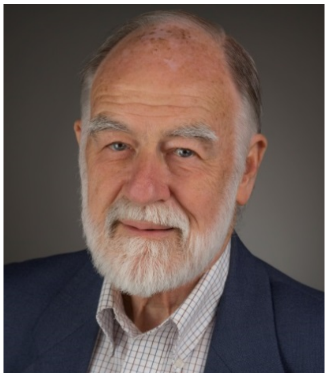
## Bang! Damage from impulse noise and the effectiveness of hearing protection


**Elliot Berger, M.S.**
3M Personal Safety Division

Elliott Berger is a Division Scientist for 3M's Personal Safety Division. For 40 years he has studied hearing protection, hearing conservation, and related topics, and authored 14 textbook chapters and over 70 published articles. He chairs the ANSI working group on hearing protector attenuation, served on a National Academy of Science committee on hearing loss in the military, is a Fellow of the ASA, Past-President of NHCA, Fellow of the AIHA and Past-Chair of its Noise Committee, a past Board Member of CAOHC, and a recipient of NHCA's Lifetime Achievement Award. Among his favorite sounds is the silvery flutter of the leaves of a stand of river birch tickled by a cool evening breeze.

Some of the most hazardous sounds we hear are brief sounds – noises from impacts and impulses. These arise from sources like household tools, construction, industrial noise, firecrackers, guns, and even automotive airbags. The progression of damage to the ear from sounds such as these differs from the gradual hearing loss due to long-term exposure to high-level noise. The various mechanisms will be revealed, as will the related damage-risk criteria for impulse noise that describe how many of those brief sounds as a function of level the ear can tolerate, before injury occurs. There still exists serious debate within the scientific community concerning such estimates and how they are derived. The other part of the story is, of course, what can be done about it? To address this, we will explore hearing protection for such noises, including how hearing protection devices are measured, how they perform, and suggestions for their use. This talk will provide you the information you need to help assure that you and those in your hearing conservation program will never have to miss what you've been hearing.

## A rationale for a national classroom acoustics standard


**John S. Bradley, Ph.D.**
Retired, National Research Council

John S. Bradley, Ph.D., recently retired from the position of Principal Research Officer at the National Research council after 40 years of working in acoustics research, mostly at NRC. His research included work on: sound insulation against outdoor aircraft noise, work on open plan office assessment and design, studies of speech intelligibility in rooms, and the rating of the speech privacy provided by rooms along with efforts to make the understanding and evaluation of performance spaces a more quantitative process. Where possible his work has included subjective evaluations of sounds as well as efforts to obtain better physical measurements. He was awarded the Sabine Silver Medal in Architectural Acoustics from Acoustical Society of America in December 2008, and the Rayleigh Medal for outstanding contributions to acoustics from the Institute of Acoustics (UK), presented in May 2011. He is a Fellow of the Acoustical Society of America and has been a member of working groups of: ISO, CSA, CGSB, ANSI, WHO, and the American Academy of Sciences. He has served as the Editor of Canadian Acoustics (3 years), the CAA Secretary, (1 year) and the President of CAA (5 years).

Although most measurement studies in classrooms have indicated ambient noise levels are too high for high quality speech communication, there are no national standards or requirements for classroom acoustics in Canada. Speech communication between a teacher and students and between students are probably the most noise sensitive activities in classrooms and are critical for maximizing the success of learning activities in classrooms. Extensive Canadian research by several Canadian researchers has identified the acoustical needs of elementary school classrooms and also has developed an understanding of the acoustical needs for university classrooms. Acoustical requirements can usually be explained in terms of obtaining adequate speech-to-noise ratios, where `speech` is the sound we want to hear and noise is other unwanted sounds including ambient noise and also some room reflections of the speech sounds. This lecture will discuss our understanding of the required acoustical conditions for classrooms based on the results of previous classroom studies and describe the particular acoustical needs of younger children. These previous results can be used to set acoustical requirements for various types of classrooms including those for younger students and others with particular special needs.

## Flow-excited acoustic resonances in shallow cavities

**Samir Ziada, Ph.D.**
Mechanical Engineering,
McMaster University,
Hamilton Ontario

Dr. Samir Ziada is a Professor at McMaster University and former Chair of the Department of Mechanical Engineering. He had 17 years of industrial experience in the Laboratory of Fluid Mechanics and Acoustics of Sulzer Innotec Ltd in Switzerland, before joining McMaster University in Canada in 1998. He has received several awards, including the Premier Research Excellence Award of Ontario, the McMaster Student Union Award for Excellence in Undergraduate Teaching and the McMaster President Award for Excellence of Graduate Supervision. Dr. Ziada's research expertise is in the areas of industrial aeroacoustics, flow-induced vibration and unsteady flows. He has published more than 200 papers, the majority of which are in the area of flow-sound interaction mechanisms and their control. He has also been invited to present several Keynote lectures in International conferences and academic institutions. He is currently a regular consultant to several industrial institutions, including the US Nuclear Regulatory Commission, Argonne National Laboratory, Brookhaven National Laboratory, among others. He served as an Associate Editor for the Journal of Fluids and Structures and the ASME Journal of Pressure Vessel Technology. Dr. Ziada is a Fellow of the ASME and the CSME and has been the Chair of the ASME Technical Committee on Fluid-Structure-Interaction.

The excitation of acoustic resonances within ducted shallow cavities is often encountered in various components of nuclear and conventional power plants, jet engines, turbo-compressors and other engineering equipment. First, the feedback excitation mechanism causing these acoustic resonances will be introduced together with the main characteristics of various acoustic modes and flow excitation sources. Attention will then be focused on how experimental and numerical techniques can be used to explore the complex flow-sound interaction patterns inside a resonant shallow cavity. Unsteady pressure measurements at various azimuthal locations within the cavity, time resolved Particle Image Velocimetry (PIV) technique, and numerical simulation of the resonant acoustic modes with the aid of finite element analysis are used to visualize the unsteady flow structures and the acoustic mode shapes. Three different interaction patterns are analyzed, corresponding to the resonance of a single stationary acoustic mode, simultaneous excitation of two different stationary acoustic modes, and a special case of spinning mode resonance due to the excitation of two degenerate acoustic modes. The results of this study substantially improve our understanding of this complex excitation mechanism and the acquired flow visualization images constitute a challenging benchmark case for the validation of Computation Aero-Acoustic (CAA) codes.

# Workshop
# Atelier

## Tools and guidelines for the calculation of apparent sound transmission class (ASTC) ratings

The 2015 edition of the National Building Code of Canada (NBCC) introduced significant changes to the requirements for the acoustic separation between dwelling units. While the requirements in previous editions of the NBCC were given in terms of the sound transmission class (STC) rating, the new requirements in the 2015 edition are given in terms of the apparent sound transmission class (ASTC) rating. The STC rating is based on laboratory measurements and only describes the sound transmission through a single building element. The ASTC rating quantifies the sound insulation of the complete building system, i.e. taking into account sound transmission through the separating element and sound transmission via flanking paths such as common floors or ceilings. The ASTC rating is therefore a better descriptor for the sound insulation that the building occupants will actually experience.

NRC·CNRC Construction

RR-331
Guide to Calculating Airborne Sound Transmission in Buildings

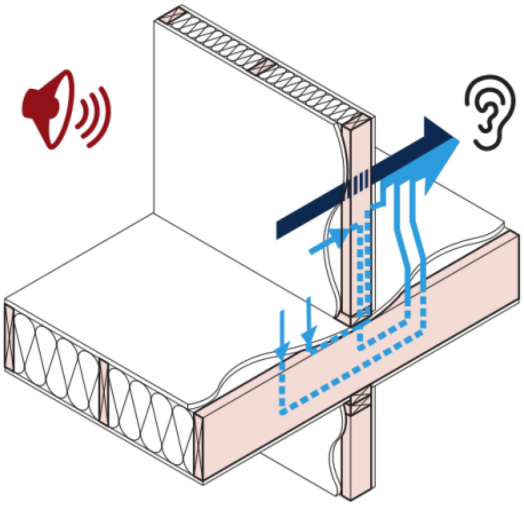
Berndt Zeitler, David Quirt, Christoph Hoeller, Jeffrey Mahn, Stefan Schoenwald, Ivan Sabourin

Second Edition
April 2016

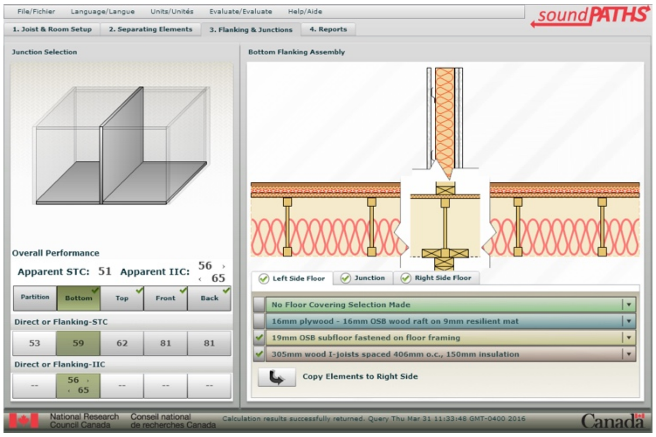
National Research Council Canada Conseil national de recherches Canada

Canada

In collaboration with Canadian industry partners, the National Research Council Canada (NRC) has developed tools and guidelines to support the transition from STC requirements to ASTC requirements. The tools and guidelines include a number of research reports which are available from the NRC Publication Archive as well as soundPATHS, the free online application for the determination of ASTC ratings of different building constructions.



This seminar will provide an overview of the new requirements in the NBCC, presenting the various ways to demonstrate compliance. The seminar will highlight the tools and guidelines developed by the NRC for practitioners, including relevant research reports and soundPATHS. The manual calculation of ASTC ratings using data from NRC reports will be demonstrated for a range of different construction types. Seminar participants will acquire knowledge about the new requirements in the NBCC and the physical basics of flanking sound transmission, and will learn where to find information and how to perform the necessary calculations to determine ASTC ratings for a range of construction types.



Overall Performance

Apparent STC: 51 Apparent IIC: 56 65

Direct or Flanking-STC

| Partition | Bottom | Top | Front | Back |
|---|---|---|---|---|
| 53 | 59 | 62 | 81 | 81 |

Direct or Flanking-IIC

| Partition | Bottom | Top | Front | Back |
|---|---|---|---|---|
| -- | 56<br>65 | -- | -- | -- |

☐ No Floor Covering Selection Made
☐ 16mm plywood - 16mm OSB wood raft on 9mm resilient mat
☑ 19mm OSB subfloor fastened on floor framing
☑ 305mm wood I-joists spaced 406mm o.c., 150mm insulation

Calculation results successfully returned. Query Thu Mar 31 11:33:48 GMT-0400 2016


**Christoph Hoeller, Ph.D.**
National Research Council

Dr. Christoph Hoeller is a Research Officer in the Acoustics Group at the National Research Council Canada. He is responsible for a range of different projects pertaining to sound transmission in buildings and human perception of sound. The current focus of his work is on supporting the transition to ASTC metrics in building regulations in Canada by developing tools and guidelines in collaboration with Canadian industry partners. Dr. Hoeller obtained an MSc from RWTH Aachen University in Germany and a Ph.D. from the University of Liverpool in the UK. He is a member of the Acoustical Society of America, the Canadian Acoustical Association, the German Acoustics Association, and the International Institute of Acoustics and Vibration. Dr. Hoeller serves on the ASTM committees on building and environmental acoustics, as well as the Canadian mirror committees for ISO standards on building acoustics.


**Jeffrey Mahn, Ph.D.**
National Research Council

Dr. Jeffrey Mahn is a Research Officer in the Acoustics Group at the National Research Council Canada. His areas of expertise include flanking transmission in buildings and measurement methods. Dr. Mahn obtained MScs from Washington University in St. Louis and the Technical University of Denmark in Copenhagen, Denmark and a Ph.D. from the University of Canterbury in Christchurch, New Zealand. He is a member of the Institute of Noise Control Engineering and the Acoustical Society of America.

| ***DAY ONE*** | ***WEDNESDAY OCT 11, 2017 - MORNING***<br>**Registration Open at 8:00, Conference Centre Foyer** | | | |
|---|---|---|---|---|
| **8:50–9:00** | **WELCOME** | | | |
| **9:00–10:00** | **Plenary: Elliott BERGER (Royal City Ballroom B)**<br>***Bang! Damage from impulse noise and the effectiveness of hearing protection*** | | | |
| **10:00–10:20** | **COFFEE BREAK (Hallway)** | | | |
| | ***OCCUPATIONAL NOISE AND STANDARDS I***<br>**Chair: Hugues Nélisse**<br>**ROOM: Gryphon** | ***ENVIRONMENTAL NOISE ASSESSMENT***<br>**Chair: Scott Penton**<br>**ROOM: Flanders** | ***ARCHITECTURAL ACOUSTICS MODELLING***<br>**Chair: Steve Meszaros**<br>**ROOM: McCrae** | ***ARCHITECTURAL ACOUSTICS APPLICATIONS I***<br>**Chair: Darron Chin-Quee**<br>**ROOM: Royal City Ballroom A** |
| **10:20–10:40** | Investigation of Ground Crew Noise Exposure for the Royal Canadian Air Force CH-149 Cormorant Helicopter (Price, Ghinet, Chen, Grewal) | Sound Power Levels and Directivity Patterns of Refrigerated Transport Trailers (Roy, VanDelden) | Room Acoustics Model Calibration: A Case Study with Measurements (Bessey, Gully, Harper) | Practical Considerations of Ontario's Tarion Builder Bulletin 19: Acoustical Reviews for New Condominium Buildings (Walters, Chin-Quee) |
| **10:40–11:00** | Occupational Health Considerations for Teachers in Music Classrooms (Seebach, Chin-Quee) | Noise Characterization and Reduction Techniques of Multiple Axial Fans Unit (Arafa, Mohany) | A Novel Approach to Counting Waves in a Room (O'Keefe) | Case Studies: Effect of Fasteners Bridging Resilient Channels on AIIC Performance in Wood-Framed Condominiums (Lalonde) |
| **11:00–11:20** | Localization of Reverse Alarms with Personal Safety Equipment (Vaillancourt, Giguère, Laroche, Nélisse) | Outdoor Concert Noise: The Kitchener ON Experience (Arnold, Chin-Quee, Penton) | Beam-Tracing Prediction of Room-to-Room Sound Transmission and the Accuracy of Diffuse-Field Theory (Mahmud, Hasan, Hodgson) | The Condominium Process and Noise (Clunis) |
| **11:20–11:40** | Hearing Protector Fit-testing: Spectrum Uncertainty Budgets (Voix) | A Barrier for Community Power Generation Close to Homes (VanDelden) | Using Generative Design Principles to Optimize the Acoustic Quality of a Meeting Room (Peters, Lamb) | Acoustic Challenges for the Pacific Autism Family Centre (Scherebnyj) |
| **11:40–12:00** | Insertion Loss of Hearing Protection Devices for Military Impulse Noise (Nakashima, Sarray, Fink) | Siting and Planning for the Ground Run-up Enclosure (GRE) at Billy Bishop Airport (Sylvestre-Williams) | The Application of NURBS to Acoustical Science (O'Keefe) | Beaver Barracks Acoustical Engineering Case Study (Clunis) |
| **12:00–12:20** | Sound Attenuation of Acoustic Shields (Behar, Luo, Mosher, Abdoli-Eramaki) | | Broadband Acoustic Energy Confinement in 3D Printed Hierarchical Sonic Crystals (Shakouri, Fan) | Destructive Interferences Created Using Additive Manufacturing (Berardi) |
| **12:20–1:20** | **LUNCH (Royal City Ballroom B)** | | | |

| ***DAY ONE*** | ***WEDNESDAY OCT 11, 2017 - EARLY AFTERNOON*** | | | |
|---|---|---|---|---|
| | ***OCCUPATIONAL NOISE AND STANDARDS II***<br>**Chair: Tim Kelsall**<br>**ROOM: Gryphon** | ***SHOCK AND VIBRATION***<br>**Chair: Al Lightstone**<br>**ROOM: Flanders** | ***EDUCATION IN ACOUSTICS I***<br>**Chair: Ramani Ramakrishnan**<br>**ROOM: McCrae** | |
| **1:20–1:40** | Going Global: Hearing Conservation Regulations and Trends (Wells) | Relationship Between Railway Ground-Borne Vibration Propagation and Track Elevation – A Field Study (Collins) | Teaching Acoustics to Psychology and Neuroscience Students (Russo) | |
| **1:40–2:00** | The History of Real-ear Attenuation at Threshold Since 1957 with Emphasis on the Most Recent ANSI S12.6-2016 and CSA Z94.2-2014 Standards (Berger) | Subway Train-induced Noise and Vibration in Buildings: Predictions and Measurements (Toome, Love) | Enseignement de L'acoustique en Conception Intégrée (Migneron, Potvin, Demers, Gosselin) | |
| **2:00–2:20** | The ISO Standard on Hearing Protectors (Behar) | Mitigation of Railway Induced Ground-borne Noise and Vibration (Alkhatib, Lightstone, Du) | Seeing Sound: A Tool for Teaching Music Perception Principles (Ng, Schutz) | |
| | ***GREEN BUILDING ACOUSTICS***<br>**Chair: Jessie Roy** | | | |
| **2:20–2:40** | Sound Transmission Loss Evaluation of Rainscreen Wall Assemblies; Investigation of Test Specimen Installation and Comparative Evaluation of 54 Rainscreen Assemblies (Connelly) | Case Study: Comparing Measured and Finite Element Modelled Footfall Vibration Levels in a New Research Building (Coetzer, Graham, Meszaros ) | Acoustics Specialization for Building Engineers (Lee, Zaheeruddin) | |
| **2:40-3:00** | Living Wall Noise - Case Study (Moquin) | Protection of Critical Assets from Construction Vibration - Field Tests, Prediction, and Control (Walters, Pridham) | Aeroacoustics and Aircraft Noise (Rocha) | |
| **3:00–3:20** | Comparison of the Acoustic Design Requirements of the LEED, WELL and Green Globes Building Rating Systems (Roy) | Effects of Cable Connections on Vibration Measurements (Lightstone, Du) | Teaching Acoustics In Architectural Programs In Canada (Berardi) | |
| **3:20–3:40** | **COFFEE BREAK (Hallway)** | | | |

| **DAY ONE** | ***WEDNESDAY OCT 11, 2017 - LATE AFTERNOON*** | | | |
|---|---|---|---|---|
| | ***ARCHITECTURAL SOUND TRANSMISSION I***<br>**Chair: Alex Lorimer**<br>**ROOM: Gryphon** | ***WIND TURBINES***<br>**Chair: Andy Metelka**<br>**ROOM: Flanders** | ***EDUCATION IN ACOUSTICS II***<br>**Chair: Ramani Ramakrishnan**<br>**ROOM: McCrae** | |
| **3:40-4:00** | Contribution of Internal Wall Assemblies to Wood-Frame Floor/Ceiling ASTC Performance (Edwards, Niinivaara, Lorimer) | Wind Turbine Aeroacoustic Noise Prediction Using Computational Models and Comparison to Experimental Measurements (Zilstra, Johnson ) | Use of Acoustical Standards in the Audiology Classroom (Giguère) | |
| **4:00-4:20** | Effect of Insufficient Adhesive on ASTC Performance in Concrete Partitions with Laminated Drywall (Niinivaara, Lorimer, Edwards) | Insertion Loss and Wind Induced Noise Results for Secondary Wind Screens (Bonsma, Gara, McCabe) | Teaching Acoustics to Architects (Ramakrishnan) | |
| **4:20-4:40** | Blocking Mass for Architectural Vibration Attenuation – A Case Study (Swallow, Villeneuve) | Differences in Predicted Far-Field Sound from Wind Turbine Noise Sources having Comparable Overall A-Weighted Sound Power Levels Using ISO 9613-2 (Clark) | Discussion | |
| **4:40-5:00** | Investigation of Flanking Noise Transmission into a Reverberation Room (Sadek, Arafa, Mohany) | Comparison of International Environmental Noise Guidelines for Wind Farms (Du, Lightstone, Doran) | | |
| **5:00-5:20** | (A)STC Testing with MLS: Old Dog. New Tricks. (Matheson) | Wind Turbine Infrasound Penetration into Homes using Narrowband Measurement Techniques (Metelka) | | |
| **5:30-7:00** | **Tours** | | | |
| **7:00-8:30** | **WELCOME RECEPTION & EXHIBITOR SHOW OPENING**<br>**(Royal City Ballroom A-B)** | | | |

| *DAY TWO* | *THURSDAY OCT 12 2017 - MORNING*<br>**EXHIBITION: Royal City Ballroom A 10:00–4:00** | | | |
|---|---|---|---|---|
| **8:35–8:40** | **OPENING REMARKS** | | | |
| **8:40–9:40** | **Plenary: John BRADLEY (Royal City Ballroom B)**<br>***A Rationale for a National Classroom Acoustics Standard*** | | | |
| **9:40–10:20** | **COFFEE BREAK (Royal City Ballroom A)** | | | |
| | ***NRC WORKSHOP***<br>**Chair: Christoph Hoeller, Jeffrey Mahn**<br>**ROOM: Gryphon** | ***HEARING SCIENCES I***<br>**Chair: Frank Russo**<br>**ROOM: Flanders** | | |
| **10:20–10:40** | Tools and Guidelines for the Calculation of ASTC (Hoeller, Mahn) | Surveying the Sounds Used in Auditory Perception Research: Journal of the Acoustical Society of America (Schutz, Gillard) | | |
| **10:40–11:00** | | Effects of Short-term Choir Participation on Auditory Perception in Older Adults. (Dubinsky, Nespoli, Russo) | | |
| **11:00–11:20** | | Upper Limits of Auditory Motion Perception with Percussion Sounds (Tarlao, Frissen, Louart, Guastavino) | | |
| **11:20–11:40** | | Brain Entrain: Acoustic Features of Music that Drive You to Synch (Nespoli, Gilmore, Russo) | | |
| **11:40–12:00** | | EARtrodes: Towards a Wireless In-ear Custom-fitted Brain Computer Interface (Valentin, Viallet, Voix) | | |
| **12:00–1:00** | **LUNCH (Royal City Ballroom B)** | | | |

| ***DAY TWO*** | ***THURSDAY OCT 12, 2017 - EARLY AFTERNOON*** | | | |
|---|---|---|---|---|
| | ***NRC WORKSHOP (CONTINUED)***<br>**Chair: Christoph Hoeller, Jeffrey Mahn**<br>**ROOM: Gryphon** | ***HEARING SCIENCES II***<br>**Chair: Jérémie Voix**<br>**ROOM: Flanders** | | |
| **1:00–1:20** | Tools and Guidelines for the Calculation of ASTC (Hoeller, Mahn) | Objective Assessment of Companding Architecture for Assistive Hearing Devices (Moshgelani, Parsa) | | |
| **1:20–1:40** | | Generating Inverse Filters for HpTF Equalization as Part of Headphone Playback of Binaural Audio (Bessey) | | |
| **1:40–2:00** | | Loudness in the Occluded Ear Canal: Are We Again Missing 6 dB? (Bonnet, Voix, Nélisse) | | |
| | | ***BIOMEDICAL ACOUSTICS AND ULTRASOUNDS***<br>**Chair: Jahan Tavakkoli** | | |
| **2:00–2:20** | | Frequency-Domain Synthetic Aperture Focusing Techniques for Imaging with Single-Element Focused Transducers (Shaswary, Tavakkoli, Kumaradas) | | |
| **2:20–2:40** | | An Image-guided Focused Ultrasound System for Generating Acoustic Shock Waves that Induce Traumatic Brain Injury in Wild-type Zebrafish (Ferrier, Kaur, Park, Liu, Baker, Tavakkoli ) | | |
| **2:40-3:00** | | Evaluation of the Bias on X-ray Absorptiometry and Quantitative Ultrasound Measurements Due to Bone-Seeking Elements (Jang, Da Silva, Tavakkoli, Slatkovska, Cheung, Pejovic-Milic ) | | |
| **3:00–3:40** | **COFFEE BREAK (Hallway)** | | | |

| ***DAY TWO*** | ***THURSDAY OCT 12, 2017 - LATE AFTERNOON*** | | | |
|---|---|---|---|---|
| | ***ARCHITECTURAL SOUND TRANSMISSION II***<br>**Chair: John Bradley**<br>**ROOM: Gryphon** | ***SPEECH SCIENCES***<br>**Chair: Bryan Gick**<br>**ROOM: Flanders** | ***ENVIRONMENTAL NOISE MODELLING***<br>**Chair: Corey Kinart**<br>**ROOM: McCrae** | |
| **3:40-4:00** | Improving ASTC Performance of As-built Wood-frame Double-shear Panel Wall Assemblies (Lorimer, Niinivaara, Edwards) | Methodological Trade-offs for Dual-purpose Phonetic Fieldwork (Percival, Bliss, Schellenberg) | Estimating Hourly Leq from 24 Hour Leq (Daly, Kelsall, Khelladi) | |
| **4:00-4:20** | Complying with High Sound Isolation Requirements in Acoustics Standards when a Suspended Ceiling Extends Continuously Over Partial-Height Demising Walls (Madaras, Heuer ) | Cross-Linguistic Bracing: A Lingual Ultrasound Study of Six Languages (Lauretta, Schellenberg, Gick) | Evaluation on Overlapping Barriers Design using SoundPLAN (Sun, Lacrampe ) | |
| **4:20-4:40** | Probabilistic Approach to Selecting a Reasonable Minimum Sample of Rooms for ASTM E-336 Testing (Bell, Haniff, Lewis, Reuten ) | Toward a Method to Uncover L1 Japanese Sociophonetic Transfer to L2 English (Yamane, Carter) | Quantitative Differences in Highway Noise Levels due to Pavement Type: Impact on Modelling Future Noise Emissions (Busch) | |
| **4:40-5:00** | The Validation of a Sound Intensity Imaging System for Wall STC Calculation, With Leak Detection (Mackenzie) | Indie-Pop Voice: How a Pharyngeal/Retracted Articulatory Setting May Be Driving a New Singing Style (Jones, Schellenberg, Gick) | Quality Assured Software Implementation of ISO 9613 According to ISO/TR 71534-3 (Hartog van Banda) | |
| **5:15–6:15** | **CAA ANNUAL GENERAL MEETING**<br>**(Room: Gryphon)** | | | |
| **6:15-9:30** | **AWC 2017 BANQUET & AWARDS (University of Guelph)**<br>**(Cash Bar open at 6:15, Banquet 19:00)** | | | |
| | | | | |

| ***DAY THREE*** | ***FRIDAY OCT 13 2017 - MORNING*** | | | |
|---|---|---|---|---|
| **8:35–8:40** | **OPENING REMARKS** | | | |
| **8:40–9:40** | **Plenary: Samir ZIADA (Royal City Ballroom B)**<br>***Flow-excited Acoustic Resonances in Shallow Cavities*** | | | |
| **9:40–10:00** | **COFFEE BREAK (Hallway)** | | | |
| | ***SPEECH COMMUNICATION***<br>**Chair: Christian Giguère**<br>**ROOM: Gryphon** | ***AEROACOUSTICS***<br>**Chair: Joana Rocha**<br>**ROOM: Flanders** | ***ENVIRONMENTAL NOISE CRITERIA***<br>**Chair: Jason Tsang**<br>**ROOM: McCrae** | ***ARCHITECTURAL ACOUSTICS APPLICATIONS II***<br>**Chair: Mehrzad Salkordeh**<br>**ROOM: Royal City Ballroom A** |
| **10:00–10:20** | Hearing and Memory Deficits in Older Adults using Telehealth (Willoughby, Zendel) | Effect of Vortex Formation Length on Flow-Excited Acoustic Resonance for a Single Spirally Finned Cylinder in Cross-Flow (Alziadeh, Mohany) | A Vital Role in Resolving Rail Related Noise and Vibration Complaints (Tsang) | Operational Transfer Path Analysis: Practical Considerations for Selecting Sensor Positions (Toome) |
| **10:20–10:40** | The Role of Inhibition in Older and Younger Adults' Lexical Competition (Colby, Poulton, Clayards) | Aeroacoustic Noise from Building Façades – Observed Problems and Approaches to Mitigation (Pridham) | Brief History of Montreal Noise-bylaws and Their Enforcement (Dumoulin) | HVAC Displacement System Noise Control – A New Method to Quantify Noise Control Performance (O'Keefe) |
| **10:40–11:00** | Sensory Integration from an Impossible Source: Perceiving Simulated Faces (Keough, Taylor, Derrick, Schellenberg, Gick ) | Wind-Induced Noise of Architectural Perforated Plates (Vanoostveen, Ziada ) | Discussion on Noise and its Impact on Birds (Babic) | Challenges in Intelligibility Analysis of Public Address and Emergency Notifications Systems (Latour) |
| **11:00–11:20** | Acoustic Analysis of Emotional Speech Processed by Hearing Aids (Goy, Pichora-Fuller, Singh, Russo) | Acoustics of Aero-Acoustic Wind Tunnels – State of the Art (Ramakrishnan, Waudby-Smith) | An Analysis of Two Cities and a State where Construction Noise and Vibration are Uniquely Regulated (Busch) | Noise Isolation Class (NIC) Testing of Modular Office Partitions (Williamson) |
| **11:20–11:40** | Voices in Noise or Noisy Voices: Effects on Task Performance and Appreciation (Bockstael, Vandevelde, Botteldooren, Verduyckt ) | Surface Dipole Strength Generated by Cylindrical Struts (Marriner) | Trading Decibels: Overview of a Cap and Trade Regulatory Framework for Noise Emissions (Lambert, Lacrampe) | Acoustic Performance of Study Rooms - A Case Study (Sagar, Ramakrishnan) |
| **11:40–12:00** | The Impact of Dialect on the Ability to Understand Speech-in-Noise (Power, Zendel) | Effect of Duct Height on the Magnitude of Acoustic Resonance for Single Cylinder in Cross-flow (Afifi, Mohany) | Standard Methods and Criteria Considerations for Residential Noise Complaints (Meszaros, Toome) | Heritage Building Conversions and Acoustics (Clunis) |
| **12:00–12:20** | An Acoustician's Journey into Hearing Aids (O'Keefe) | Development of Aircraft Cabin Sound Environment Reproduction Facility for Passenger Comfort Research (Yapa, Ghinet, Price, Grewal, Chen, Wickramasignhe ) | Discussion | |
| **12:20–1:40** | **LUNCH & STUDENT PRESENTATION AWARDS (Royal City Ballroom B)** | | | |

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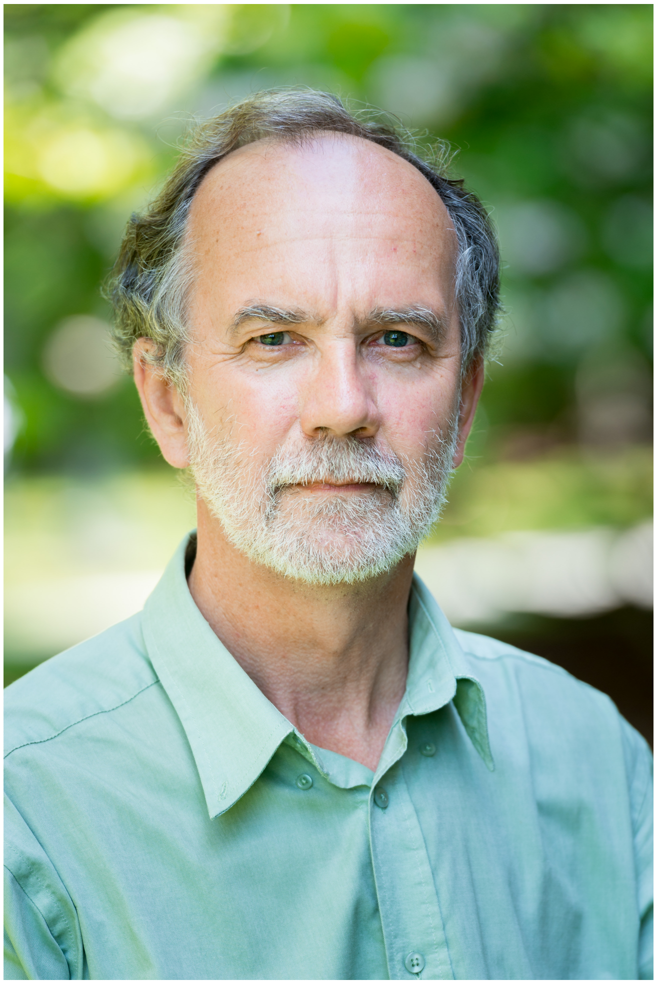
# Professor Murray R. Hodgson
# Professeur Murray R. Hodgson

It is with great sadness that we share the news that our friend and colleague Dr. Murray Hodgson passed away on August 19th 2017 at UBC's St. John Hospice.

Murray joined UBC in 1991 as the first Workers' Compensation Board endowed chair hired for a new graduate program to train occupational hygienists, the professionals who evaluate workplace exposures and design methods to control them. He was a key contributor to the program's growth and evolution, and served as its director from 2000 to 2002. He had joint appointments in Mechanical Engineering and Population and Public Health, and was principal investigator and director of the Sustainable Building Science Program from 2011 until his death.



Before joining UBC, Murray conducted research at Herriot-Watt University in Edinburgh, the University of Sherbrooke, and the National Research Council of Canada. He received his PhD from the University of Southampton and post-doctoral training at Cambridge.

Murray's research focused on the measurement, characterization, prediction, and control of sound fields in rooms – especially industrial workshops, offices, classrooms, and health-care facilities. He led the elucidation of the existence and characteristics of non-diffuse sound fields, and was one of the earliest developers of software for predicting noise in classrooms and industrial plants. Murray was also a wonderful collaborator who had joint projects in other engineering disciplines, education, environmental sustainability, audiology, and language sciences with colleagues at UBC, across Canada, and elsewhere in the world. His research renown was recognized via editorships of five acoustics journals, awards from the Canadian Acoustical Association and the Acoustical Society of America, many keynote lectureships, memberships on expert advisory committees, and diverse consultancies on acoustical issues.

Murray's research was multidisciplinary in scope and so was his teaching. He was known for his teaching excellence and for the wide range of students he reached. As the only UBC faculty member with expertise in engineering and architectural acoustics, he developed and taught full courses for public health and engineering students, and provided lectures and short courses for students and professionals in architecture, audiology, mining-engineering, and physics.

Murray was passionate about the impact of noise on people – their health and wellbeing, and their ability to communicate, develop, and learn. There are few who are unaffected by noise as a public health problem, but sadly too few who attempt to understand and mitigate it. Murray's work will have a lasting impact from locally at UBC where he helped design acoustically-appropriate learning spaces, to globally through his software, acoustic evaluations, publications, and most importantly, his graduates.

Hugh Davies and Kay Teschke,
School of Population and Public Health,
University of British Columbia


EFFECTIVE
SOUND
MASKING

# AEROACOUSTICS - AÉROACOUSTIQUE

# EFFECT OF DUCT HEIGHT ON THE MAGNITUDE OF ACOUSTIC RESONANCE FOR SINGLE CYLINDER IN CROSS-FLOW

**Omar Afifi** *1 **and Atef Mohany** †1
[1]AeroAcoustics and Noise Control Laboratory, University of Ontario Institute of Technology, Oshawa, Ontario, Canada.

## 1 Introduction

Flow-excited acoustic resonance is a major concern in many industrial applications, such as in tube bundles of heat exchangers, due to its harmful effects. If not treated, flow-excited acoustic resonance may lead to excessive cycling vibrational loads on the tube bundles, which could subsequently result in premature failure of equipment. Even when structural failure is not a concern, the high tonal noise associated with the acoustic resonance can be damaging to human ears and may exceed the allowable federal/provincial noise regulations.

Due to the complex nature of the flow-sound interaction that occurs between packed tubes of heat exchangers, no unified model has been proposed to date for prediction or supression of flow-excited acoustic resonance. Moreover, more research has recently focused on studying simplified models, such as single [1,2], tandem [3], and side-by-side cylinders [4], that exhibit flow-sound characteristics similar to those of tube bundles to fully understand and characterize the underlying physics of the phenomena. In an attempt to successfully develop a unified acoustic resonance prediction model, this paper studies the effect of the duct height on the self-excited acoustic resonance mechanism of single bare cylinders in cross-flow for the first acoustic mode.

It is known that the acoustic resonance in ducts containing single cylinders occurs when the frequency of vortex shedding from the cylinder matches one of the natural frequencies of the duct, $f_v = f_a$ , and when there is enough energy in the flow to overcome the acoustic damping of the system.The natural acoustic frequency of the system is related to the duct height according to the equation $f_a = nc/2h$, where $n$ is an index referring to the acoustic mode of interest (i.e. 1, 2, 3 .. etc.), $c$ is the speed of sound, ~343m/s, and $h$ is the height of the duct. Therefore, by changing the duct height, the frequency at which acoustic resonance occurs changes. The change in the resonance frequency was found to greatly affect the magnitude of acoustic pressure amplitudes at resonance, even at cases when the dynamic head $(0.5\rho U^2)$ at coincidence is the same.

## 2 Experimental setup

Experiments outlined in this paper are conducted in an open-loop wind tunnel facility made up of several sub-parts as indicated in Figure 1. Three different test-sections with heights of 203, 254 and 305 mm were built for the experiments. The natural frequencies of the ducts are 845, 675, 562 Hz respectively. The width and depth remained contant with values of 127 and 762 mm respectively. The air velocity inside the test section is controlled through a centrifugal blower that is connected to an electric motor with a variable frequency driver (VFD). Maximum air-velocity attained by the current setup is ~165 m/s.

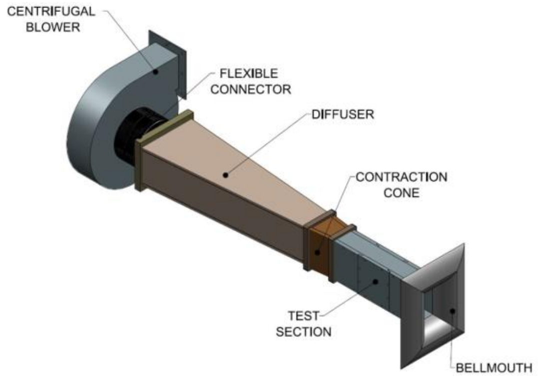


**Figure 1:** Isometric CAD view of the wind-tunnel assembly at the AeroAoustics and Noise Control Laboratory (UOIT)

Seven smooth aluminmum cylinders with varying diameters in the range of 10 – 25 mm were used in the present work. All cylinders were rigidly attached at the center of each test section, to excite the first acosutic cross mode of the duct. The acoustic pressure generated inside the duct was measured using a ¼-inch pressure michrophone manufactured by PCB piezotronics. The microphone was rigidly fixed and flush-mounted at the top wall of the test section at fixed distance from the center of the cylinder. The location of the microphone was set to 25.4 mm downstream the cylinder centerline. This location was determined in a seperate experiment. Figure 2 shows a schematic side-view of the test section showing measurment locations.

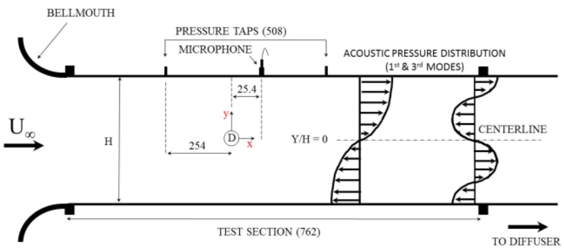


**Figure 2:** Schematic of the test section showing the position of the measurment devices (all dimensions in mm)

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## 3 Results and discussion

For the sake of brevity, only the acosutic response of the cylinders is presented for discussion. The upstream air velocity and pressure are presented in Pa and m/s.

In order to investigate the effect of the duct height, cases are compared where the cylinder diameter is constant while the height is varied. Figure 3 shows the acoustic pressure response of a cylinder with diamter 21.05 mm tested in all ducts. It is observed that the acosutic pressure amplitude produced by the cylinder at resonance is proportional to the duct height. The cylinder in the tallest duct height produced an acoustic pressure of 1108 Pa, while when the same cylinder was placed in the middle and shortest duct heights it produced acoustic pressure amplitudes of 654 Pa, and 565 Pa respectively.

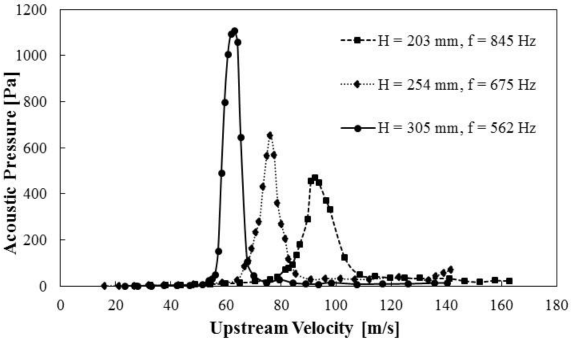

**Figure 3:** Pressure response for cylinder diameter D = 21.05 mm.

Special cases with similar blockage ratio (D/H) were also investigated. For an equal blockage ratio the resonance occured at the same velocity for all the cases. For example, for the blockage ratio of 6.25%, theoritically all cases should have the velocity of coincidence at 54 m/s. Experimentaly the three cases had the velocity at resonance coincidence at the values of 59, 56 and 57 m/s. However, the highest duct produced significantly hgiher acoustic pressure amplitude at resonance.

Figure 4 shows the pressure response for a blockage ratio of 6.25% presented in all ducts, for the first acosutic mode. It can be observed that the three cases behave similarly in terms of onset and off-set of acosutic resonance, however the acosutic pressure amplitude increases with the increasing duct height.

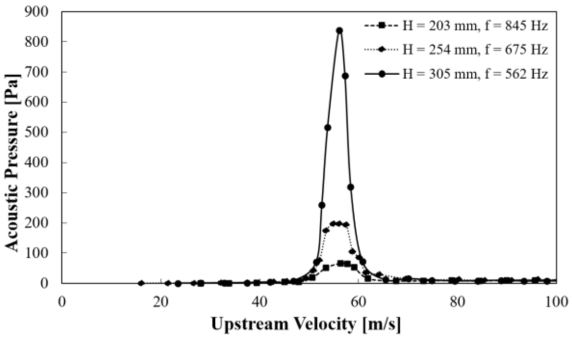

**Figure 4:** Pressure response for blockage ratio of 6.25%

The difference in acoustic pressure amplitudes despite equal input energies can be attributed to the acoustic attenuation. Acoustic attenuation of sound in ducts occurs due to multiple energy loss mechanisms such as viscosity, heat conduction, turbulence, and convection. In ducts, the acoustic damping is mainly due to the visco-thermal losses within the pipe/duct [5]. Quantifying the visco-thermal losses at the duct walls when a sound wave is propagating can be quantified using the first order model of Kirchhoff, expressed by the equation below.

$$\alpha_o = \frac{l}{2A_s c_o} \sqrt{\frac{\pi f \mu_{dynamic}}{\rho}} \left(1 + \frac{\gamma - 1}{\sqrt{Pr}}\right)$$

This equation takes into account the cross sectional area of the duct, as well as other heat parameters that remained constant in the presented cases. From the equation it can be concluded that the visco-thermal damping coefficient varies in proportional to the square root of the frequency which is affected by the duct height.

## 4 Conclusion

The effect of changing the duct height on the acoustic pressure amplitude for single bare cylinders in cross-flow has been investigated. It has been shown that changing the duct height alters the acosutic characterstics of the system such as the damping and stiffness, which results in different pressure amplitudes at resonance even for cases where the input energy, quantified by the dynamic head, is equal. The results of experiments discussed in this paper shows that the acoustic damping of the duct is an important parameter that may have been overlooked in the past and should be included in prediction criteria proposed for complex geometries such as tube bundles of heat exchangers

## Acknowledgments

The authors thankfully acknowledge the financial support provided by the Natural Science and Engineering Research Council of Canada (NSERC).

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# EFFECT OF VORTEX FORMATION LENGTH ON FLOW-EXCITED ACOUSTIC RESONANCE FOR A SINGLE SPIRALLY FINNED CYLINDER IN CROSS-FLOW

**Mohammed Alziadeh** *1 **and Atef Mohany** †1
1Aeroacoustics and Noise Control Laboratory, University of Ontario Institute of Technology, Oshawa, Ontario, Canada.

## 1 Introduction

The sound generation from vortex shedding over bluff bodies has been the focus of numerous research studies over the past century. The vortex shedding caused by fluid cross-flow over bluff bodies confined inside an enclosure can cause excitation of the enclosure's acoustic modes. This occurs if the flow-excitation energy is adequately high enough to overcome the losses due to acoustic damping [1]. This mechanism is the cause of flow-excited acoustic resonance, a phenomenon that is a major design concern in many engineering applications.

There have been many investigations conducted to characterize and understand the complicated flow-sound interaction mechanism in heat exchanger tube bundles. These investigations have been undertaken by breaking up the intricate geometric configuration of tube bundles into simplified cases, such as single, tandem, side-by-side, inline or staggered array bare cylinders [1–4]. These investigations have provided extensive insight on the complex flow-sound interaction mechanism of bare cylinders arranged in various configurations. However, with the exception of [5], [6], the flow-sound interaction mechanism of finned cylinders has never been investigated. Furthermore, these investigations were limited to finned cylinders with straight (annular) fins. Therefore, in this study, the flow-sound interaction mechanism of spirally finned cylinders in cross-flow was investigated.

## 2 Experimental setup

The experimental apparatus consists of an open loop wind tunnel that is connected to a centrifugal air blower. The wind tunnel consists of a parabolic bell mouth, test section, diverging diffuser, and a flexible connection. The test section is manufactured out of 19.05 mm thick acrylic panels, with duct dimensions of 254 mm high and 127 mm wide. The aeroacoustic response measurements were performed by utilizing a 6.35 mm pressure microphone that was flush-mounted 25.4 mm downstream of the cylinder centerline, as this position corresponded to the point where the highest acoustic pressure was measured. The vortex formation length was calculated by measuring the velocity fluctuation along the wake centerline. This was done through the use of a single hot-wire probe, installed on a traverse mechanism. The vortex formation length was measured before the resonance condition to avoid damaging the hot-wire probe.

To understand the flow-sound interaction mechanism of spirally finned cylinders, three crimped spirally finned cylinders with different fin spacing were investigated. The measurements obtained for the case of the finned cylinders were compared to bare cylinders with the same equivalent diameter. The equivalent diameter was calculated using a modified version of equivalent diameter equations presented in the literature. The modification was done to take into account the added flow blockage imposed by the fin crimps. A schematic of the spirally finned cylinder with important fin parameters labelled is shown in Figure 1. The dimensions of the finned cylinders are listed in Table 1. The finned cylinders were tested while horizontally mounted at the center of the duct test section, as it corresponds to the position of the acoustic particle velocity anti-node of the fundamental acoustic cross-mode of the duct. The acoustic particle velocity is essential to the flow-acoustic coupling during flow-excited acoustic resonance.

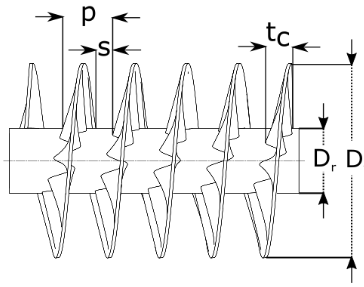

**Figure 1:** Schematic of crimped spirally finned cylinder.

**Table 1:** Dimensions of spirally finned cylinders. Dimensions listed in millimeters (mm).

| | Fin I | Fin II |
|---|---|---|
| Root Dia., $D_r$ | 12.7 | 12.7 |
| Fin Dia., $D_f$ | 38.1 | 38.1 |
| Fin Pitch, $p$ | 9.8 | 4.9 |
| Fin Spacing, $s$ | 6.8 | 3.1 |
| Total Fin Thick., $t_c$ | 3.0 | 1.8 |
| Mod. Equiv. Dia., $D_{eq}$ | 20.4 | 25.3 |

## 3 Results

### 3.1 Vortex formation length

Figure 2 shows the velocity fluctuations ($u'$) measured along the wake centerline ($Y/D_{eq} = 0$). The vortex formation length is the point where the maximum velocity

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fluctuation is measured along the wake centerline. As shown in Figure 2, the bare cylinder exhibits the shortest vortex formation length. With the addition of spiral fins with large fin spacing, the vortex formation length increases. However, reduction in the fin spacing causes the vortex formation length to progressively decrease, approaching that exhibited by the bare cylinder.

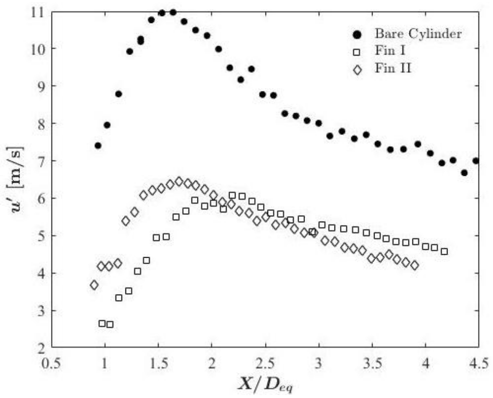

**Figure 2:** Velocity fluctuations measured along the wake centerline ($X/D_{eq} = 0$) at $Re_{Deq} = 3.5 \times 10^4$.

### 3.2 Aeroacoustic response

Figure 3 shows the normalized aeroacoustic response of all the finned cylinders compared against their equivalent diameter bare cylinders. It can be seen that the finned cylinder with the largest fin spacing (Fin I) has the lowest generated acoustic pressure during acoustic resonance excitation. Moreover, the gap between the peak acoustic pressure measured during resonance for the case of Fin I to that of its equivalent diameter bare cylinder is quite substantial. Reduction in the fin spacing causes a significant increase in the acoustic pressure generated during acoustic resonance excitation, as well as a reduction in the peak acoustic pressure difference between the finned cylinder and its equivalent diameter bare cylinder. In all cases, however, the acoustic pressure generated during acoustic resonance excitation for the bare cylinders were higher than that of their equivalent finned cylinders.

## 4 Discussion

As has been shown in Figure 2, the addition of spiral fins elongate the vortex formation length. This increase is associated with an early shear layer formation and separation, which causes the separated flow to be convected further downstream, leading to the formation of vortices further away from the cylinder base. With reduction in the fin spacing, the point of flow separation is progressively delayed, leading to a shorter vortex formation length. During acoustic resonance excitation, cylinders that exhibit a smaller vortex formation length produce higher peak acoustic pressure. This is because the flow-acoustic coupling will occur closer to the cylinder base, which is where the acoustic particle velocity is maximum.

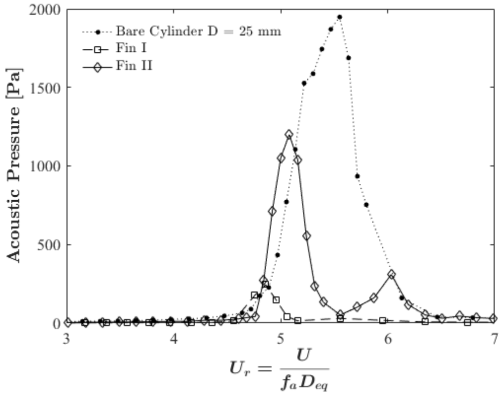

**Figure 3:** Normalized aeroacoustic response of finned cylinders compared to their equivalent diameter bare cylinders. $U$ = Flow velocity, $f_a$ = Fundamental acoustic cross-mode.

## 5 Conclusion

The effect of the spiral fins on the vortex formation length, and its consequence on the flow-sound interaction mechanism was studied. It was found that spirally finned cylinders elongate the vortex formation length as compared to their equivalent diameter bare cylinder. Reduction in the spiral fin spacing lead to a gradual decrease in the vortex formation length. This has shown to influence the peak acoustic pressure during acoustic resonance excitation, where cases that exhibited a relatively smaller vortex formation length generated higher acoustic pressure during resonance excitation.

## Acknowledgments

The authors would like to express their appreciation for the financial support provided by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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# SURFACE DIPOLE STRENGTH GENERATED BY CYLINDRICAL STRUTS

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## 1 Introduction

The generation of noise by flow past rigid surfaces has been the subject of considerable speculation and controversy. This paper considers the spatial distribution of the acoustic dipole source strength over the surface of a rigid cylindrical strut located in a coannular cold subsonic air flow using the causality cross-correlation technique.

## 2 Method

### 2.1 Surface dipole strength by cross-correlation

The acoustic radiation $p'(x_i,t')$ at receiver point $x_i$ emanating from a region of unsteady flow containing an embedded surface is given by a simplification of Curle's generalized solution of the Lighthill equation [1]. The equation below assumes the Mach number is low, surfaces are stationary, shear stresses are negligible and λ<< surface dimension:

$$p'(x_i,t) \simeq \frac{x_i}{4\pi x^2 c_\infty} \int_S n_i \left[ \frac{\partial}{\partial \hat{t}} p'_S(y_i,\hat{t}) \right]_{\hat{t}=t-r/c_\infty} dS(y_i) \qquad (1)$$

Where $n_i$ is the unit normal to surface S at surface point $y_i$, r is the distance of sound travel from any given point on surface S to the receiver $x_i$ and $c_\infty$ is the celerity of sound.

The mean square pressure at $x_i$ may be formed by multiplying equation 1 by the $p'(x_i,t')$ and taking ensemble averages, or alternately, equivalent time averages assuming the flow parameters are ergodic random functions of time The result is shown in equation 2 below [2] :

$$\overline{p'p'}(x_i) \simeq \frac{-x_i}{4\pi x^2 c_\infty} \int_S n_i \left[ \frac{\partial}{\partial \hat{\tau}} \overline{p'_S(y_i)\,p'(x_i)}\;(\hat{\tau}) \right|_{\hat{\tau}=r/c_\infty} dS(y_i) \qquad (2)$$

Introducing the source and receiver sound pressure levels (SPLs), the above may be written in differential form giving the distribution of surface dipole strength over surface S. The result is shown in equation 3 below:

$$\frac{d\overline{p'p'}}{dS}(x_i,y_i) \simeq \frac{-x_i\,n_i(y_i)}{4\pi x c_\infty} \left[ \frac{\partial}{\partial \hat{\tau}} \overline{C}(x_i,y_i)\;(\hat{\tau}) \right]_{\hat{\tau}=r/c_\infty} \qquad (3)$$

$$p^2_{REF}\ \text{antilog}_{10} \left\{ \frac{SPL(y_i) + SPL(x_i)}{20} \right\}$$

Where $\overline{C}(x_i,y_i)$ is the dimensionless causality cross-correlation coefficient for surface dipoles evaluated at the Kirchoff delay time $\hat{\tau}$ as shown in equation 4 below:

$$\overline{C}(x_i,y_i)\;(\hat{\tau}) = \left[ \frac{\overline{p'_S(y_i)\,p'(x_i)}\;(\hat{\tau})}{p_S^{RMS}\quad p^{RMS}} \right]_{\hat{\tau}=r/c_\infty} \qquad (4)$$

The source and far field RMS pressures may be obtained from their respective autocorrelation functions evaluated at time zero.

### 2.2 Description of flow

Potential flow issuing from a coannular cold jet of air incident on a cylindrical strut separates from the strut at point s shown in Figure 1. The flow velocity at the jet nozzle exit plane was 72 m/s and the Reynolds number based on strut diameter was 6.4 x $10^4$ for the analysis herein. Flow separation at s induces a periodic side force at the Strouhal vortex shedding frequency of 1.13 kHz [3].

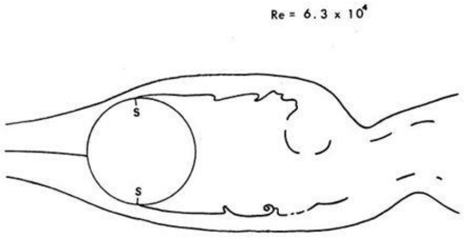

**Figure 1:** Incident potential flow separates at s (Source unknown)

### 2.3 Procedure to evaluate surface dipole strength over the surface of the strut

A strut measuring 12.7 mm in diameter and 170 mm in length and was drilled out to accommodate a one quarter inch Brüel & Kjær (B&K) Condenser Microphone Type 4136 connected to a B&K Preamplifier Type 2618 forming a source region probe. The microphone cartridge was sealed in the small cavity by an O-ring, The O-ring was positioned between the microphone membrane and the relief vent as shown in Figure 2.

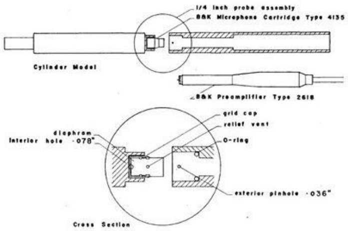

**Figure 2:** Cylindrical strut with ¼ inch microphone probe

The air-filled cavity in front of the membrane was coupled to the surface of the cylindrical strut by a tiny capillary tube terminating at a surface pinhole. The tube measured 0.91 mm (0.036 in) in diameter at the surface of the strut and was 3.18 mm in length. The probe configuration essentially behaved as a Helmholtz resonator. These two Helmholtz parameters and volume were

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optimized to extend the high frequency response of the probe and minimize the phase shift at the highest frequency of interest at the receiver (measured to be 4000 Hz, Re = 6.3 x $10^4$). Cotton fibers were added to dampen the amplitude of the resonance peak. It was found the cylindrical strut fitted with a one eighth inch B&K Type 4138 microphone performed slightly better than a one quarter inch B&K Type 4135 microphone probe and introduced less phase shift (approximately one degree at 4000 Hz).

The pinhole on the strut surface was moved into different positions in the flow of the potential core of a cold air jet by varying ϕ and h (see Fig.3) to determine $p'(y_i,t)$.

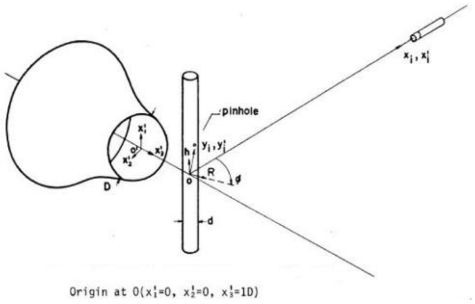

**Figure 3:** Cylindrical strut at potential core

## 3 Results

Spectra of the acoustical pressure $p'$ were measured at surface point $y_i$ given by (R=d/2,ϕ=0,h=0) and free field receiver point $x_i$ given by ($x_1$=0,$x_2$=-3m,$x_3$=0m). Peaks emerged from spectra at the center frequencies listed in Table 1.

**Table 1:** 1/3 octave center frequencies of spectral peaks

| Acoustical pressure | 1/3 octave band center frequency (Hz) |
|---|---|
| Surface $p'(y_i)$ | 1250 |
| Receiver $p'(x_i)$ | 1250 |

Generating a circumferential profile of the surface dipole strength over a strut cross section involved evaluating equations (3) and (4). Cross correlations and auto correlations were generated from 24 measurements of $p'(y_i)$ and $p'(x_i)$ swept through successive ϕ with h=0.

$\overline{C}(x_i, y_i)$ $(\hat{\tau})$ was evaluated using (4) at each position from which surface dipole strength was found by taking the slope of $\overline{C}(x_i, y_i)$ at the Kirchoff delay time $(\hat{\tau})$. Profiles resulting from (3) are depicted in Figure 4.

## 4 Discussion

Vortex shedding at the characteristic Strouhal frequency is evident from the Table 1. The spectrum of surface pressure in the potential core exhibited a peak within the one-third octave band centered at 1250 Hz. The peak was likely due to vortex shedding at the Strouhal frequency. Irregular turbulence superimposed on the vortices together with spanwise variation of the mean incident velocity acted to broaden the Strouhal peak.

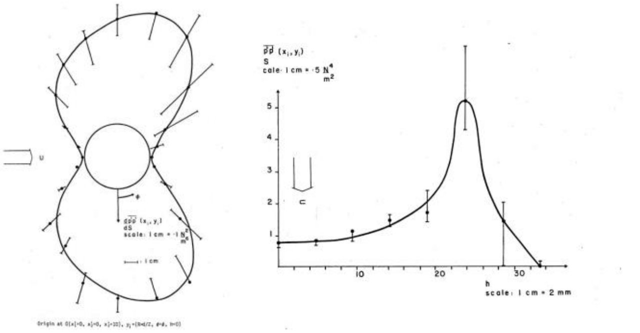

**Figure 4:** Circumferential profile of surface dipole strength (left) with spanwise profile inset (right)

The overall SPL at $x_i$ measured 70.1 ± 0.5 dB, an increase of 20 dB over that before the strut was introduced into the flow. The observed increase is caused by the boundary obstructing the aerodynamic flow and inducing stress fluctuations in the neighboring fluid which formed dipole sources on the surface of the strut.

The circumferential profile of surface dipoles measured at a series of 24 points at midspan shown in Figure 4 bears the shape of $\cos^2 ϕ$ arising from two factors: surface geometry introduced a cos ϕ factor; a fluctuating lift force introduced an additional cos ϕ factor. Uncertainty is indicated by the error bars in Figure 4 and was largely due to uncertainty in the exact Kirchoff delay time.

The spanwise profile of surface dipoles (Figure 4 inset) was also measured, at a series of 10 points from midspan along the strut's lateral edge. The two profiles were used to approximate the complete surface dipole distribution over the strut. The surface integral of the dipole strength over the strut was found to be 67.0 to 71.7 dB, comparing favorably with the measurement of 70.1 ± 0.5 dB at the receiver.

## 5 Conclusions

The causality cross-correlation technique provided an efficient means for obtaining diagnostic information and insight on the mechanisms of aerodynamic noise generation. In this case, evidence of vortex shedding was found. The overall noise at the receiver $x_i$ was predicted by integrating two surface dipole profiles for the strut.

## Acknowledgments

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# ACOUSTICS OF AERO-ACOUSTIC WIND TUNNELS – STATE OF THE ART

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## 1 Introduction

Wind tunnels continue to be used extensively for the development of aerospace vehicles and ground vehicles. An area seeing continued growth is in aero-acoustic testing. For ground vehicles, primarily cars and SUVs, the emphasis is on interior noise sources, though the exterior background sound field must be sufficiently low. The main focus of this paper is a general description of the aero-acoustic aspects of wind tunnels. The resulting noise characteristics and progression through time of the achieved background noise level with each new wind tunnel are then summarized.

## 2 Wind tunnels

A schematic detail of open-jet closed loop configuration of a wind tunnel for aero-acoustic purposes is shown in Figure 1.

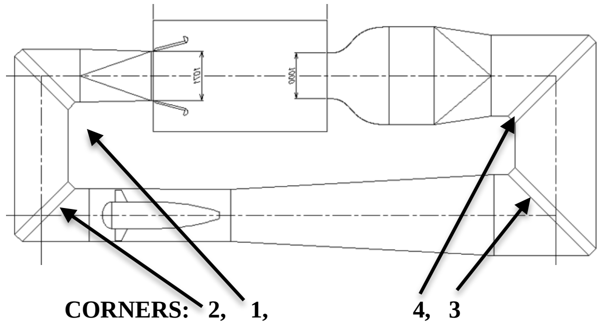

**Figure 1:** Configuration of an open-jet, closed loop tunnel.

In a closed loop tunnel, there are four sections of the circuit, starting with the test section, two corners, fan section and two more corners with the required diffusion and contraction to provide a smooth flow within the test section. In addition, a heat exchanger with arrays of tubes (finned or not) is usually installed in the settling chamber upstream of the nozzle contraction to remove the heat generated by the fan.

## 3 Noise sources

The main noise source in any wind tunnel is the main fan, which is usually an axial fan, with strong low frequency components. The flow speeds at Corners 1 and 2 can be high and mid-to-high frequency noise would be generated by the turning vanes.

Control methods to reduce the noise levels are: a) silencers upstream and downstream of the fan; b) lining the turning vanes with absorbent materials; c) lining the duct surfaces with noise reduction materials; and d) lining the open jet test section walls with acoustic wedges or thick absorbent panels [1 - 3]. The acoustic treatment attenuate the fan noise sufficiently such that local noise sources in the test section become significant. Noise levels generated by various sources are shown in Figure 2 [4].

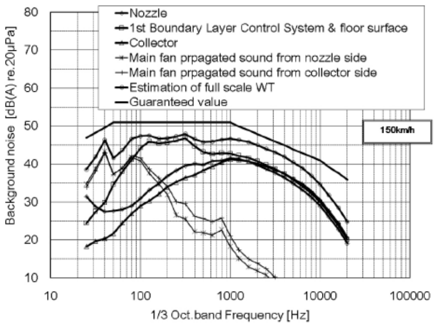

**Figure 2:** Predicted noise levels of Toyota's 1/10th model tunnel [4].

Strong Aeolian tones will be generated at set frequencies by the heat exchanger tubular array. Depending on the location of the heat exchanger, the tones can be amplified if they coincide with the standing wave resonant frequencies of the wind tunnel section. The resulting sound levels can be as high as 140 dB at the Aeolian tone coinciding with the standing wave resonance. The impact of shedding vortices and settling chamber resonances are highlighted in Figure 3. Different measures such as flow blocking at resonance anti-node locations and acoustic treatment are required to eliminate these tones.

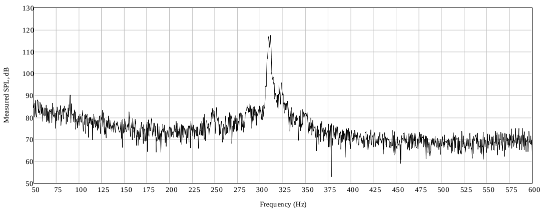

**Figure 3:** Measured sound spectrum adjacent to a heat exchanger during resonance.

Another resonance phenomenon that can impact the test section noise levels is from coupling of the shear-layer fluctuations with resonance modes in the circuit, primarily full-circuit organ pipe modes and the nozzle collector

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feedback mechanism (vortices shed from the nozzle impacting the rear of the test section and feeding back to the nozzle). These “organ pipe” modes result in very low-frequency resonances of the order of several Hz for full-scale automotive wind tunnels. Even though inaudible, the circuit resonance can disturb the flow substantially. Methods developed to minimize these resonances include the use of nozzle exit vortex generators (to alter the frequency of the shed vortices), inducing entrained air from outside to flow through the test section (to lessen the shear layer strength), active noise control, and the use of passive Helmholtz resonators [3]. A sample circuit resonance event, at 2.3 Hz, and attenuation using a Helmholtz resonator are shown in Figure 4 below.

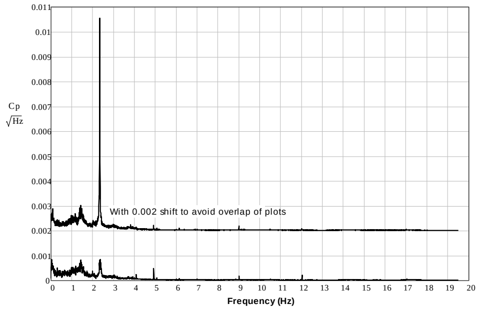

**Figure 4:** Circuit resonance (upper line) and with resonator (lower line)

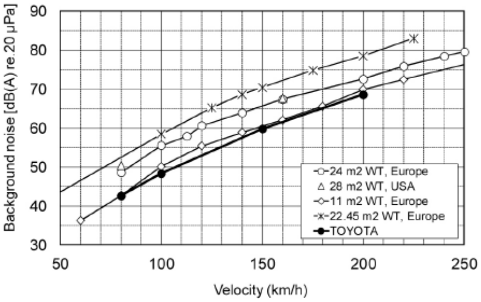

**Figure 5:** Test section OASPLs of a set of aero-acoustic tunnels [4].

## 4 Acoustical requirements

The increasing demand for acoustic testing of vehicles has led to a continuing reduction of the background noise in the test section as can be seen in the Figures 5 and 6 [data from references 4 thru’ 13]. The more recent wind tunnels, and specifications for new ones, represent diminishing returns for noise suppression within the wind tunnel. The primary noise sources remaining are from the boundary layer, especially the boundary layer reduction system, and the flow at the collector (at the rear of the test section). There are indications that the new automotive acoustic wind tunnels are quiet enough to meet the demands for acoustic testing, at least at present [6, 12]. Improved noise measurement techniques such as 3D beamforming with simultaneous interior measurements could further diminish the need for additional background noise reductions in the test section.

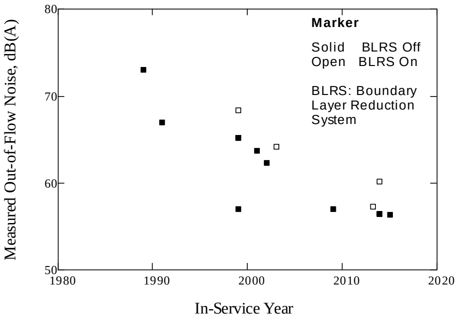

**Figure 6:** Chronological improvement to out-of-flow OASPLs in automotive aero-acoustic tunnels. Measurement locations not entirely consistent. Wind speed = 140 m/hr

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# WIND-INDUCED NOISE OF ARCHITECTURAL PERFORATED PLATES

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## 1 Introduction

Perforated plates are a common architectural feature which are known to produce noise when exposed to high winds. For certain conditions, this noise can be highly tonal and audible, which is an annoyance for inhabitants of the building.

Extensive work has been done in the literature to study flow over perforated plates at perpendicular or parallel angles of incidence. Flow through a perforated plate or orifice at a perpendicular direction may produce tonal noise due to an unsteady shear layer separating at the upstream corner of the orifice and impinging on the downstream corner. This effect occurs only for sharp-edged holes with a diameter of 1 to 2 times their length (*D/t* = 1-2). [1]

Similarly, parallel angles of incidence, or grazing flow, have been studied by many researchers for a variety of geometries, including perforated plates, orifices, and cavities. The case of tonal noise generation by grazing flow over a perforated surface is investigated in reference [2], with further details found in the works cited therein. In general, these tones are generated by the periodic impingement of vortices on the downstream corner of the holes. This periodic impingement causes a feedback which is felt upstream, leading to the repeated initiation of vortices at the upstream edge. This mechanism may be coupled with resonant or elastic effects, but can also occur purely due to the fluid dynamics.

Only a few researchers have looked at flow over perforated plates at oblique angles of incidence, where an oblique angle is defined as any angle which is not a multiple of 90°. This is important for architectural applications, since the direction of the wind is naturally varying. As an example, in reference [3], tonal noise was identified for flow over perforated plates at angles of incidence, θ, of 10° to 30° from parallel.

## 2 Method

### 2.1 Experimental apparatus

A simplified model of a perforated plate is used in this investigation. The circular holes of a typical perforated plate are replaced by a series of long rectangular slats with an adjustable gap width between them. This simplified model is studied experimentally in a wind tunnel for various angles of incidence and flow velocities. A cross-sectional view of the experimental apparatus is shown in Figure 1.

Four variables can be changed to study their effect. First, the gap width between the slats can be adjusted. The slats can also be replaced with a standard perforated plate for validation of the results. Second, the mean velocity of the wind tunnel can be changed by adjusting the speed of its blower. Third, the angle of incidence of the plate can be changed by pivoting about a hinge at the edge of the wind tunnel outlet. Fourth and finally, the microphone position can be changed in the *X*, *Y*, and *Z* directions.

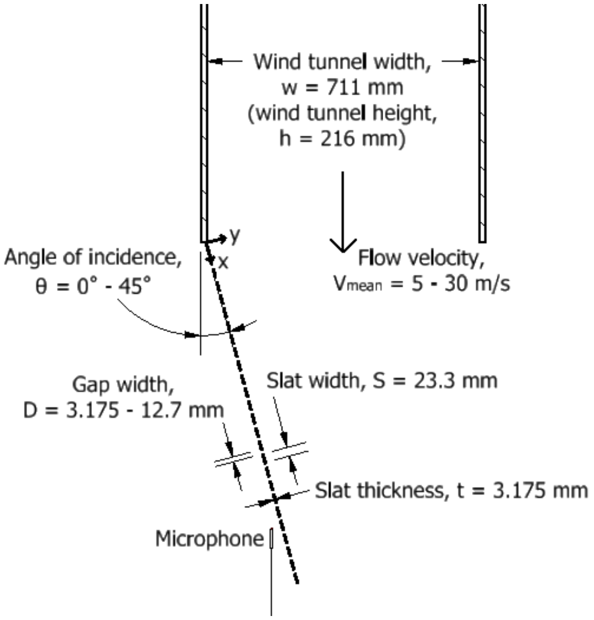

**Figure 1:** Experimental apparatus consisting of a series of rectangular slats mounted on an angle at the exit of an open circuit wind tunnel.

### 2.2 Acoustic measurements

A G.R.A.S. microphone, preamplifier, and power supply are used to measure the acoustic response of the test plates under various input conditions. The microphone is positioned 25.4*mm* from the back of the plates in the *Y*-direction and is moved by a traverse to various positions in the *X*-direction. For each test case, the microphone signal is recorded for 5 minutes at a sampling rate of 5000*Hz*, and the average frequency spectrum over that sampling window is calculated.

The frequency spectra are expressed using the dimensionless Strouhal number, *St*, where $V_{mean}$ is the mean flow velocity, $f$ is the frequency, and $d$ is the characteristic dimension.

$$St = \frac{f * d}{V_{mean}} \qquad (1)$$

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For a perforated plate, *d* is defined as the hole diameter. For the rectangular slats, *d* is defined as the gap width multiplied by a factor of *(4/π)*.

### 2.3 Particle image velocimetry

Phase-locked particle image velocimetry (PIV) is used to calculate the velocity field between the slats. The flow is seeded with bis (2-ethylhexyl) sebacate particles and illuminated with a laser sheet positioned on the backside of the slats (negative *Y*-direction in Figure 1). A camera is positioned above the apparatus (*Z*-direction in Figure 1) to capture images of the area between the slats.

The images are phase-locked to the dominant tonal peak using the same microphone system as the acoustic measurements. Two-hundred images are taken at each phase, and the average flow field is calculated for each.

## 3 Results and discussion

### 3.1 Acoustic results

In Figure 2 below, the results of this research are compared with the results from literature. The black lines are the results of Feng [3] for θ = 15° and V = 15*m/s* for plates with a thickness of 1.5*mm* and 5 different hole diameters. For all cases, a peak is observed at a frequency of 2000 to 2500*Hz*. Using the experimental apparatus in Figure 1 and a perforated plate with a thickness of 1.5*mm* and a hole diameter of 6.35*mm*, a tone is produced at the same frequency as the results from literature. This is shown by the red line in Figure 2. The amplitudes of the results are not comparable due to different levels of background noise, different experimental apparatuses and different microphone locations.

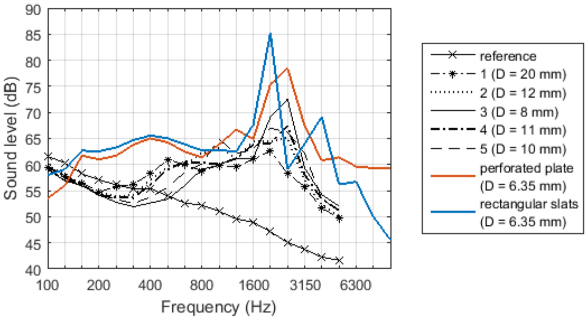

**Figure 2:** Acoustic results for θ = 15° and V = 15m/s. The black lines are the results of Feng [3], and the colored lines are the results of this research.

The blue line in Figure 2 is for the two-dimensional model with a gap width equal to 6.35*mm*. The frequency of the largest peak is 2000*Hz*. This is slightly lower than the peak produced by the perforated plate. However, when the correction *(4/π)* is applied, *St* is very similar. Both the perforated plates and the two-dimensional model produce tones for angles of incidence between 5° and 30°. For both, there is an optimal angle between 15° and 25° which produces the largest tonal peaks. For angles larger or smaller than optimal, the frequency of the peaks remains the same, but the magnitude decreases. The optimal angle is larger for smaller hole diameters or gap widths.

Similarly, there is an optimal velocity at which tonal noise is produced for a given geometry. This optimal velocity is greater for smaller hole diameters or gap widths.

### 3.2 Particle image velocimetry results

Figure 3 shows the vorticity field for a single phase for the case of θ = 15° and V = 20*m/s*. The black lines are contours of the $d_2$ parameter, which identifies vortices in the flow field [4]. Vortices form in the unsteady shear layer originating from the upstream slat and impinge on side of the downstream slat. At the downstream corner, these vortices separate into vortex pairs, where one half has positive vorticity and the other half has negative vorticity. These vortex pairs have a frequency equal to that of the measured tonal noise, and are therefore responsible for this noise.

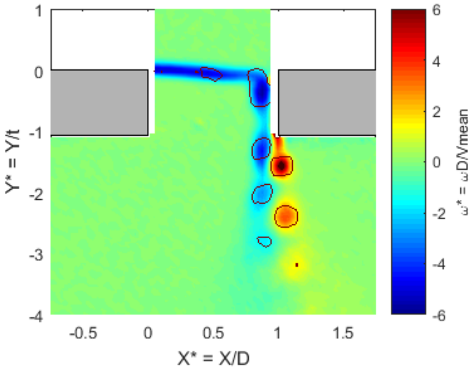

**Figure 3:** Particle image velocimetry results for θ = 15° and V = 20m/s.

## 4 Conclusion

For flow over perforated plates at oblique angles of incidence, tonal noise is produced at θ = 5° to 30°, with the optimal angle and velocity depending on the plate geometry. At the optimal conditions, this tonal noise is produced by the periodic shedding of vortex pairs at the trailing edge of the holes.

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# ABSTRACTS FOR PRESENTATIONS WITHOUT PROCEEDINGS PAPER
# RÉSUMÉS DES COMMUNICATIONS SANS ARTICLE

## Aeroacoustic Noise From Building Façades – Observed Problems And Approaches To Mitigation

*Brad Andrew Pridham*

As wind passes over and around a building there are aerodynamic interactions between the airflow and building features. This includes local accelerations of flows, the generation of turbulence, and the potential formation of vortices in the wake of building features. Under certain conditions this interaction can result in the generation of audible tones. If the amplitude of the generated tone is sufficiently high, and its characteristics are distinctly different from the existing background noise level, disturbance to the building and its surrounding environment is possible. Several phenomena are attributed to the generation of aerodynamic noise. Many of these relate to physical conditions that are often exploited in musical acoustics to produce an efficient generation of sound by coupling airflow or vibration to a resonant object. Whereas in musical acoustics the instruments are tuned to produce specific pitch and timbre, conditions of aerodynamic noise generated by buildings are generally unexpected, unwanted, and unmusical. When these problems occur, they often become publicized due to noise complaints, and can lead to loss of revenues, costly remediation, and potential damage to the reputation of the building owner and designers. As such, there is a desire to identify risk during the design of the building and take appropriate steps to mitigation of risk where noise generation is possible. In this presentation we discuss the common sources of aeroacoustic resonances that occur on building façade features, some of the techniques used to establish risk of noise problems, and approaches to managing risk and mitigation measures. Examples are presented from projects around the globe that include some of the world's tallest buildings. Numerical and experimental methods of assessment are reviewed and a general framework for assessment is presented.

## Development Of Aircraft Cabin Sound Environment Reproduction Facility For Passenger Comfort Research

*Upekha Senarath Yapa, Sebastian Ghinet, Andrew Price, Anant Grewal, Yong Chen, Viresh Wickramasignhe*

The Cabin Comfort and Environment Research (CCER) facility is a flexible cabin laboratory at National Research Council of Canada (NRC), which was built to investigate the effects of integrating new cabin technology and designs on passenger comfort and travel experience. The cabin sound field reproduction system is one of the capabilities being developed within the CCER in order to accurately reproduce the spatial distribution of the sound field environment within an aircraft cabin that passengers experience during flight. Sound environment reproduction in aircraft cabin mock-up can be used to demonstrate novel cabin interior technologies, and is also critical for maximizing the realism of flight experience when human subjects are used in experiments. This paper describes the progress of the current capability development to reproduce aircraft cabin interior sound field inside a full-scale cabin mock-up. A 40 channel microphone array was built and used to capture in-flight sound recordings of representative flight segments of the NRC Falcon 20 aircraft. The CCER cabin mock-up will be used to reproduce the spatial distribution of the cabin sound field using mini-actuators mounted on the cabin trim panels. Material characterization and modal analysis of the cabin trim panels were conducted through simulations on LMS VirtualLab and validated through experimental tests. The spatial distribution of the aircraft cabin sound pressure levels reproduced using the developed system will be compared with the original recorded sound field within the NRC Falcon 20 aircraft cabin.

# ARCHITECTURAL ACOUSTICS - ACOUSTIQUE ARCHIRECTURALE

# INVESTIGATION OF FLANKING NOISE TRANSMISSION INTO A REVERBERATION ROOM

**Omar Sadek** [*1], **Nadim Arafa** [†1] **and Atef Mohany** [‡1]
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## 1 Introduction

Testing facilities such as reverberation rooms or anechoic chambers are prone to flanking noise transmission problems. Flanking noise is the noise transmitted through indirect paths in buildings. These indirect paths, known as flanking paths, can be in the form of structural elements such as ducts, doors, ceilings, or floors of a building (structural-borne) or to be non-structural paths as air ducts, electricity outlets, and air leakage through holes or cracks in walls (air-borne). Flanking transmission can strongly affect the sound insulation between rooms in a building. Usually, the sound transmission through each flanking path is less than the direct transmission between two rooms. However, as there are many flanking paths, the overall flanking transmission is often important in sound transmission [1]. In buildings with masonry and concrete walls, around 50% of the sound transmission between two rooms is contributed by the flanking transmission and the rest is by the direct transmission through the common dividing partition [2]. If there is no common dividing partition between the source room and the receiver room, then all sound transmission is because of flanking paths [3].

Eliminating these paths requires a proper isolation of the room. However, in some cases leakage may occur despite the measures taken in their design and construction. Therefore, an accurate acoustical assessment is required to sort out the possible flanking paths and evaluate the main contributing paths to the leakage. In this work, detailed characterisation of flanking noise transmission into an industrial reverberation room is presented. Moreover, a mitigation technique was implemented to reduce/eliminate the flanking noise transmission into the reverberation room. The industrial reverberation room under consideration is located within a manufacturing facility.

## 2 Method

The characterization process inside the factory is done in two stages. First, acoustic noise measurements were performed inside and outside the reverberation room to characterise the acoustic field distribution in the facility and recognize the potential flanking noise paths. Second, a thoroughly examination of each flanking path is carried out to estimate its weighted contribution to the overall noise leakage.

The reverberation room under investigation has overall dimensions of 37 x 31 x 27 ft and separated from the rest of the facility by a separation wall composed of acoustic insulation filling sandwiched between two 10 gauge metallic sheets. The ceiling is a metal deck while the floor is made from concrete. The separation wall is equipped with air vents with integrated acoustic silencers to facilitate the introduction of air flow during the acoustic measurements. The reverberation room is connected via a duct to the acoustic source room. Free field microphones were used to measure and map the acoustic field inside the reverberation room and outside in the vicinity between the acoustic source room and the reverberation room. Precautions were considered in order to neutralize the effect of standing waves during the acoustic field measurements. Also, multiple accelerometers were used to measure the structural-borne flanking transmission at different locations. A special analyzing code was developed to match or to correlate the signals acquired from different measuring transducer, e.g. matching the signals of accelerometers and the microphones, to properly inspect the contribution of each flanking path. This matching process was based on the statistical correlation coefficient *R(f)*.

## 3 Results and discussion

### 3.1 Acoustic noise measurements

This stage was carried out at two times; during a regular working day and during a weekend day when the manufacturing facility is not operating. From comparing the measurements obtained from both days, it was evident that the outside noise leaks into the reverberation room at the low bands (f < 100 Hz). This leakage seemed to be not transmitting through the metallic separation wall as had been previously expected due to air vents. To investigate this further, white noise was introduced into the room, and the overall sound pressure levels (OSPL) inside and outside the room were measured as shown in Figure 1. It is clear that there is high leakage at frequencies less than 100 Hz which confirms the flanking transmission.

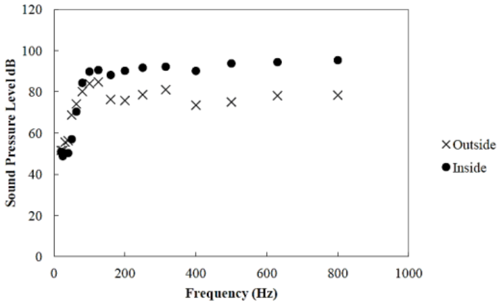

**Figure 1 :** Sound Pressure Level comparison between inside and outside the reverberation room.

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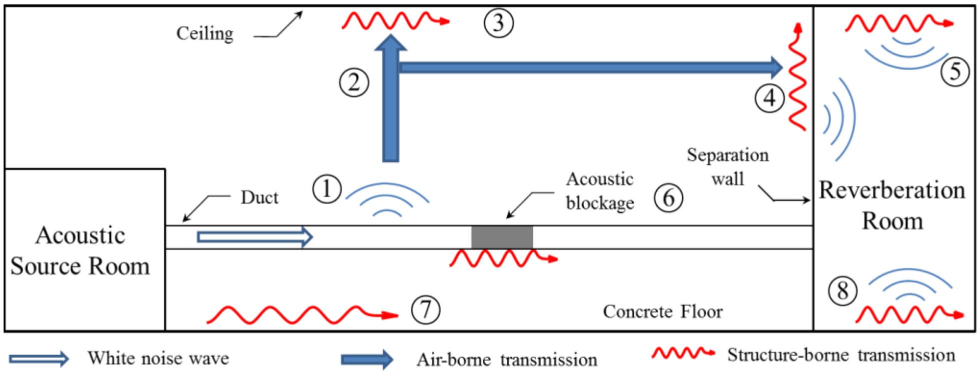

**Figure 2 :** Sketch of the elevation view with the expected flanking transmission paths for the reverberation room zone in the factory.

Another test was set by acoustically blocking the direct path of the white noise through the duct via acoustical insulating pads. This blockage forces the acoustical energy to pass through the flanking paths to the reverberation room. The OSPL inside the room was relatively at the same levels as without blockage while the OSPL outside the room was around 5 dB higher than the value inside at frequencies ≤50 Hz. This indicates that flanking transmission is the major contributor to this sound leakage at the mentioned frequency range.

The potential flanking transmission paths are illustrated in figure 2. There are three main structural flanking paths. First, the path along the duct body itself and crosses the two sides of the separation wall then to the room (1-6-4-room). Second, the path from the duct body to the outer separation wall then the ceiling and after that the room (1-6-4-5-room). Third, the flanking transmission through the floor from the source to the room (source-7-8-room). The paths which include air-borne transmission (paths 1-2-4 and 1-2-3) are considered as secondary flanking paths because of the high acoustic losses due the reflection of acoustic waves while transmitting through different mediums.

## 3.2 Structural vibration measurements

The structural vibration was measured via a set of accelerometers placed at different positions on the duct, separation wall, ceiling, and its supporting beams. The correlation coefficient of their signals and the microphone signals were calculated. Figure 3 plots such correlation from various transducers referenced to the signal from the accelerometer located at the outer side of the separation wall. High correlation values indicate better matching between the signals and they are more likely to be linked to each other. It can be seen that there is a weak correlation between the two accelerometers placed on both sides of the wall, hence the less likelihood of sound emission from the wall. This agrees with to what was found from the acoustic noise measurements. The high correlation value at 60Hz is due to the electrical noise. Other correlations were investigated. They revealed that ground flanking path (7-8) is not a main contributor. Surprisingly, a relation was found between the ceiling's supporting beams and the noise inside the room at frequencies ≤100 Hz even when the duct was disconnected which suggested that secondary path 1-2-3-5-room is the main flanking path. A solution was implemented to weaken this flanking path, and acoustic noise measurements were repeated. The repeated measurements showed that the flanking noise was successfully reduced by 10 dB at the frequency bands 25 Hz, 31.5 Hz, 40 Hz, and 50 Hz, and less reduction was obtained for higher bands.

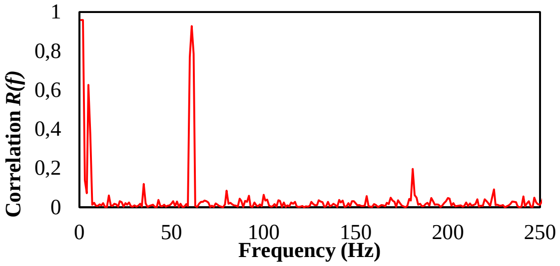

**Figure 3 :** Correlation between the signals of the accelerometers placed on the outer and inner side of separation wall.

# 4 Conclusion

A flanking noise investigation into an industrial reverberation room was carried out. It consisted of two stages. The first is an acoustic field mapping inside and outside the reverberation room to recognize the potential flanking transmission paths. The second is the detailed "Correlation" or "Matching" analysis to find out the relation strength between structural vibration and acoustic field at several points along the paths. The analysis revealed that the path 1-2-3-4-room is the major structural-borne flanking path. The propped solution showed a 10 dB reduction in the flanked transmission at frequencies less than 50 Hz.

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# PROBABILISTIC APPROACH TO SELECTING A REASONABLE MINIMUM SAMPLE OF ROOMS FOR ASTM E-336 TESTING

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## 1 Introduction

Large buildings or multi-building complex designs include a multitude of partition performance requirements, construction types, and floor plan configurations. One may therefore be faced with potentially assessing hundreds of wall and ceiling design variations with varying sound reduction performance requirements. For one recent project, the RWDI design team was faced with helping a client design and assess performance of approximately 10,000 rooms within a multi-building complex.

Partition constructions varied between STC 45 and STC 60+. Testing was carried out on the STC 50, 55 and 60+ constructions, with the intention that STC 45 walls would typically be built using STC 50 rated constructions. The project specifications required testing of a large sample of the partitions to verify their performance, however the standard of acceptable performance was not well defined. The biggest issue with the testing requirements was a lack of applicable validation criteria to provide confidence in the tested partitions being representative of the remaining partitions in the complex. As a result, RWDI proposed using a statistical approach to minimizing the number of total rooms tested, while providing a specified level of confidence in partition performance for the whole building.

## 2 Method

### 2.1 Acoustical testing method

There are three main metrics for evaluating the sound transmission performance of a partition. These include STC (Sound Transmission Classification), FSTC (Field Sound Transmission Classification) and ASTC (Apparent Sound Transmission Classification).

STC is a laboratory rating under ideal conditions, typically used for selecting partition constructions during design. FSTC was not chosen due to the minimum room size for testing and the stringent requirements necessary to control flanking paths before proper testing can be conducted. ASTC was used as it includes the effects of flanking paths under normal usage while allowing the removal of flanking sounds through doorways by means of door plugs. This approach allowed testing to be conducted during construction before all finishes were complete or doors were installed.

The testing method required for this project was to follow ASTM E-336 [1] as applicable.

### 2.2 Statistical method

The project specification originally required that 5% of all partitions be tested. For a project this size with approximately 10,000 rooms, the number of partitions to be tested was estimated to be between 500 and 1000, which was not practical. A new confidence method/criteria needed to be designed for this size of project to provide confidence to the client and owner that the partitions were constructed to the proper standard.

Thus, a probabilistic approach based on Bayes' Theorem was developed. Bayes' Theorem was applied to calculate the probability that a given percentage of all rooms fail, based on test results of a random sample of partitions. The solution is a continuous distribution that is directly proportional to the hypergeometric distribution (Gregory [2]). The approach took in several factors that included:

- The tolerance for risk is given by the percentage of the credible region (95%), which can be adjusted based on the risk tolerance.
- The failure rate (the percent of rooms permitted to fail the test) was set at 10%, but can be adjusted.
- The failure threshold is incorporated via the specified variance tolerance, which was set at 5 STC points below the specified laboratory STC rating.

The hypergeometric distribution requires as input the sample size, the measured failure rate in the sample, the total number of partitions, and the acceptable failure rate. The limit of the credible region is determined from the area underneath the probability distribution. The statistical approach provides a means of estimating the overall expected "Pass/Fail" rate for all partitions in the project. The goal of the testing and remediation program was to achieve at least 95% probability (tolerance for risk) that no more than 10% (failure rate) of the entire population of partitions are below the targeted ASTC rating (failure threshold). In other words, through this analysis, we can state that we are 95% confident that at least 90% of the partitions in the building will achieve the desired performance level.

For this statistical approach to work, the selected partitions must meet the following conditions:

- Randomly sampled (i.e. not selected by those involved with the construction);

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- Representative of different wall types, room types, and wall configurations (i.e. with different mullion and penetration conditions, column locations, duct layouts, recessed panels, etc.); and
- Relatively evenly distributed throughout the complex (i.e. from various stages of construction, different construction crews, variations in materials or construction practices, etc.).

Another advantage of the statistical approach is the ability to assess a small sample of tests while partitions are being constructed, and to compare the results to previous testing rounds. This method was used to correct construction practices and ensure continual improvement throughout construction. This feedback allowed the contractors to understand the faults during construction and fix all similar and future constructions. When failing partitions were fixed, the resolved issues were retested and re-incorporated into the statistical model. This process requires close communication and cooperation among the acoustics consultant, the construction manager and the construction teams. Nevertheless, the alternative is significant re-work and post-construction mitigation.

The example below for a population size of 450 partitions total shows several rounds of testing and continuous improvement until the statistical requirements above were met.

**Table 1:** Example of statistical analysis applied to population of 450 partitions.

| Activity | Partitions Tested | Failed | Median Failure Rate | Upper 95% Confidence Failure Rate |
|---|---|---|---|---|
| First round of tests | 8 | 1 | -- | -- |
| **Cumulative** | **8** | **1** | **18%** | **43%** |
| Second round of tests | 12 | 1 | -- | -- |
| **Cumulative** | **20** | **2** | **12%** | **27%** |
| Mitigation for one partition type | -- | -1 | -- | -- |
| **Cumulative** | **20** | **1** | **8%** | **20%** |
| Third round of tests | 20 | 1 | -- | -- |
| **Cumulative** | **40** | **2** | **6%** | **14%** |
| Mitigation for one partition type | -- | -1 | -- | -- |
| **Cumulative** | **40** | **1** | **4%** | **11%** |
| Fourth round of tests | 20 | 0 | -- | -- |
| **Cumulative and Final** | **60** | **1** | **2%** | **7%** |

# 3 Acoustical testing

## 3.1 Initial visit

An initial site visit was completed by RWDI staff during early construction of partitions, with only a few rooms constructed and no finished ceilings, doors, or furnishings within the room. The testing identified construction deficiencies for the contractors to improve. The main deficiencies observed were typical flanking paths at penetrations and perimeter joints (i.e. at slab and window mullions), with little attention to construction of proper acoustic details. The client was informed of the deficiencies, and these were corrected in both the existing partitions and in all future partitions. This was part of the continual improvement aspect of the testing plan to help the client improve construction quality while striving to meet the new testing criteria.

## 3.2 Follow-up visits

Several more site visits were made to the site to conduct further sample testing to populate the statistical model and eventually satisfy the testing program criteria. These tests were usually completed after confirmation that the client had attempted to rectify any earlier failures so that the statistical model could be updated. As before, the results of the testing were provided to the client so that failures could be investigated and corrected as construction of the complex progressed.

# 4 Results

In the end, far fewer than 5% of the rooms required testing. Meeting the above statistical model parameters required a total of 243 tests conducted on 196 different partitions. These numbers illustrate that re-testing of several partitions was required. The total breakdown included:

- 120 partitions with a design rating of STC 50;
- 60 partitions with a design rating of STC 55;
- 14 partitions with a design rating of STC 60+; and
- a check of 2 partitions with a STC 45 target.

The majority (169) of the partitions passed on their first test. Of the remaining, 22 partitions required very minor remediation before passing on their second test. Finally, there were 5 partitions that required multiple tests and deeper investigation into their reduced ASTC performance.

# 5 Discussion

The above statistical method resulted in a significantly reduced sample of partition tests to meet the client's requirements, and provided sound statistical evidence that untested rooms would be expected to meet the design requirements. The testing procedure also allowed for continual improvements to construction practices to be implemented.

One drawback to this statistical method for testing, is that until sufficient passing tests have been completed, the total number of tests required to meet the statistical validation is not known. Therefore, we found that scoping and planning the proper timing and number of site visits was quite difficult. However, the probabilistic approach provides a statistically based response for an acceptable number of partitions to be tested in a large building or complex with varying STC requirements, wall types, and wall configurations. Weighting these benefits versus the drawback, we found this approach to be superior to agreeing on a fixed sample size (number of partitions to be tested) prior to testing.

# References

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# DESTRUCTIVE INTERFERENCES CREATED USING ADDITIVE MANUFACTURING

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## 1 Introduction

The broad absorption of low-frequency noise typically requires the utilization of large thicknesses of sound absorbing materials. As this creates space issues, there is a demand for thin broad low-frequency absorbers. This research aims to develop an acoustic panel for low-frequency broad sound absorption. For this scope, passive destructive interference resonance tubes were created through the project "*Architectonics Using Destructive Interference Acoustics*". As the work deals with complex geometries, the ability of digital fabrication to enable design freedom and to support the production of complex geometries was explored.

Sound-absorbing technologies are often constrained by conventional techniques represented by porous absorption, typical of energy-dissipative materials, and reactive absorption, typical of vibrating panels and perforated ones. However, another way to absorb a sound is by generating destructive interference reflections, a principle generally used in active noise control applications [1].

Destructive interference means that two interfering sound waves that are in counter-phase, cancel each other. Digital fabrication may play an important role in developing customized sound absorbing components capable of generating destructive interference reflections below 500 Hz. The innovative samples were inspired by recent studies using 3D manufacturing for creating highly absorbing materials [2]. The project consisted in developing and testing various prototyping methods via digital fabricated prototypes, after having encoding rules for the geometric design generation.

## 2 Previous studies

In order to have destructive interferences, it must be created a pathway open at both ends that provide two entry points for the soundwaves, so that at some point within the tunnel, the waves will be at 180˚ phase difference resulting in cancelling each other out [3]. The benefit of this strategy is that it does not require active components to reduce noise.

For a sound path tube with destructive interferences, Setaki et al. presented a set of formulas to calculate the frequency of maximum absorption [2]. This is inversely proportional to the tube length ($f=(2n-1)c/2L$), so that a long tube is required to absorb low frequency. Meanwhile, Cai et al. focused on the design of coplanar Helmholtz resonators using quarter-wavelength resonance tubes [3]; this last design is a tube with a single hole of entry for the soundwave and with a rigid termination at the other end of the tube to generate an out-of-phase reflection. Cai et al. found that the opening of the tube contributes to most of the damping due to the friction loss [3].

## 3 Methodology

The results of the studies of Costa [4] were used to calculate the length and radius diameter of the tubes for low frequency absorption. Table 1 shows the parameters of the absorbers that were tested. As evident the tubes had to have a significant length, especially for absorbing at frequencies below 200 Hz.

**Table 1:** Geometrical characteristics of the created resonators.

| Frequency (Hz) | Radius (mm) | Path length (mm) | Frequency (Hz) | Radius (mm) | Path length (mm) |
|---|---|---|---|---|---|
| 100 | 8.4 | 850 | **250** | **7.2** | **340** |
| **125** | **8.2** | **680** | 315 | 6.9 | 270 |
| 160 | 7.8 | 531 | 400 | 6.6 | 210 |
| 200 | 7.4 | 425 | **500** | **6.5** | **170** |

A parametric script using Grasshopper through Rhinoceros where the parameters could be changed to create a new resonance tube was created. Due to goal of testing the resonators within the impedance tube, the overall diameter of the module had to be 10 cm. This raised the challenge of efficiently organizing the resonance tube while still limiting the overall depth of the absorber. Figure 1 shows the modules that were designed. Originally, the two openings proved to be in odd locations, e.g. close to each other (see the 250 Hz sample). Thinking to assembly more resonators together, these openings would create clustered holes with large spacing in between; the openings were hence spread toward the edge to create a more uniform pattern if more absorbers are put together. Then, the optimal setup to increase the path density within the cylindrical volume was searched: this ended having three central circles surrounded by a ring of more circles to allow both ends of the tube on the top face.

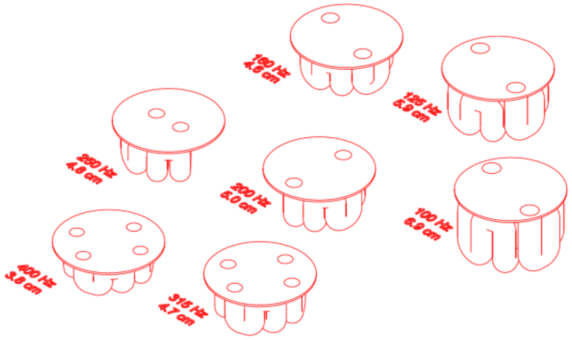

**Figure 1:** Drawings of the investigated sound absorbers.

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Figure 1 shows that each system had a different depth, from 3.8 cm up to 6.9 cm. For the aesthetics, the openings of the resonance tubes were considered fairly distributed.

The equipment used for the fabrication of the modules was a Dimension SST 1200es. This 3D printer model uses Fused Deposition Modelling (FDM), a technique that takes solid filament and heats it at the head. The model is fabricated layer by layer as the melted filament is extruded and hardens. The printed layers accumulate and harden over each other, culminating in a finished model. FDM requires a secondary soluble material used as temporary structural support which is removed after the printing is submerged into hot water. One aspect about the FDM that needs to be kept in mind is that the layering nature of the FDM method causes slight undulations on the sides of the tubes, so the resonator walls may present some air pockets within each layer which may cause sound leakages and anomalies in its acoustic behavior (Fig.2).

**Figure 2:** Photos of the 3D printed passive resonators.

The material used for this study was low-density ABS plastic. It was decided to investigate if the acoustic results were caused by the modules having one or two openings per tube. This prompted an investigation on how sealing one end of the tube could affect the performance of the modules. Based on the three fabricated modules (Fig.2), with theoretical maximum absorption at 125 Hz (#2), 250 Hz (#1), and 400 Hz (#3), 2 mm thick plates were fabricated so that they could be attached to the face allowing to cover one of the openings.

## 4 Results and conclusions

An impedance tubes was used for the testing the effectiveness for the three samples in Fig.2. Table 2 reports their one-third octave band sound absorption coefficients.

Figure 3 shows the sound absorption behaviour. The results show that the untapped samples result in high absorption than when a single hole (two in the case of sample #3) was open. This may partially be explained by the increase availability for the sound to travel into the tube, but it is clearly an effect of the resonance created in the tube. As evident the untapped samples (higher number of holes), especially for the sample #2, show sound absorption peaks in general agreement with the theoretical expectations. Although, the strong peaks, the absorption coefficients in Table 2 still result in low values. Future work will consider to create square panels arranging different resonance tubes and targeting different frequencies to investigate how multiple modules perform together.

**Table 2:** Sound absorption results for the samples in Fig. 2 (in bold the frequency where the maximum absorption is expected).

| Frequency (Hz) | Sample 1 *(2 central holes)* | | Sample 2 *(2 edge holes)* | | Sample 3 *(4 edge holes)* | |
|---|---|---|---|---|---|---|
| | 1 hole | 2 holes | 1 hole | 2 holes | 2 holes | 4 holes |
| 100 | 0.07 | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 |
| 125 | 0.35 | 0.25 | 0.26 | **0.19** | 0.23 | 0.24 |
| 160 | 0.52 | 0.39 | 0.39 | **0.26** | 0.24 | 0.29 |
| 200 | 0.55 | **0.61** | 0.36 | 0.21 | 0.18 | 0.27 |
| 250 | 0.40 | **0.53** | 0.31 | 0.25 | 0.17 | 0.20 |
| 315 | 0.33 | **0.48** | 0.51 | 0.19 | **0.15** | 0.13 |
| 400 | 0.37 | 0.48 | 0.22 | 0.47 | **0.36** | 0.14 |
| 500 | 0.39 | 0.44 | 0.25 | 0.18 | **0.54** | 0.14 |
| 630 | 0.26 | 0.55 | 0.20 | 0.14 | 0.28 | 0.19 |
| 800 | 0.26 | 0.37 | 0.18 | 0.12 | 0.18 | 0.64 |
| 1000 | 0.26 | 0.48 | 0.25 | 0.26 | 0.15 | 0.19 |
| 1250 | 0.19 | 0.37 | 0.25 | 0.18 | 0.43 | 0.08 |
| 1600 | 0.22 | 0.31 | 0.21 | 0.12 | 0.17 | 0.09 |
| 2000 | 0.17 | 0.20 | 0.00 | 0.03 | 0.61 | 0.19 |
| 2500 | 0.39 | 0.48 | 0.42 | 0.43 | 0.31 | 0.45 |

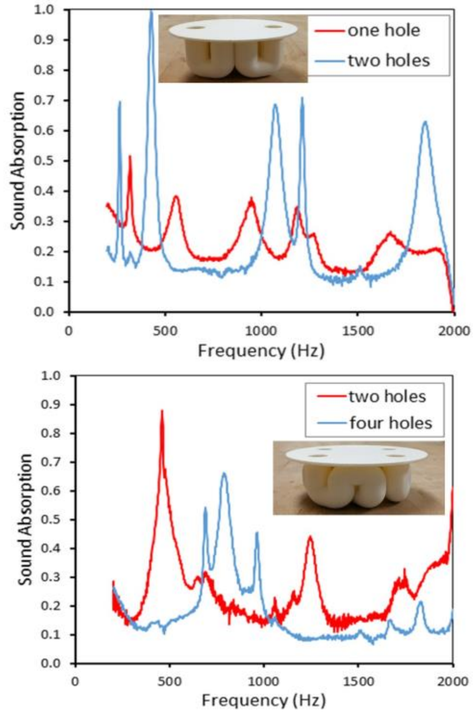

**Figure 3:** Sound absorption results for samples #2 and #3.

## References

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[3] X. Cai, Q. Guo, G. Hu and J. Yang. Ultrathin low-frequency sound absorbing panels based on coplanar spiral tubes or coplanar Helmholtz resonators. *AIP*, 105th, 2014.

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# ROOM ACOUSTICS MODEL CALIBRATION: A CASE STUDY WITH MEASUREMENTS

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## 1 Introduction

Poor classroom acoustics can result in low levels of speech intelligibility, cause stress for both teachers and students, and detract from the overall education experience. While typical classroom finishes like acoustical ceiling tile and wall panels provide a means of absorbing sound, these are less suitable in speciality classrooms like construction workshops, specialized laboratories, and culinary arts teaching kitchens.

Due to complaints of poor speech intelligibility in a wine-tasting classroom built with kitchen finishes, an acoustical investigation was conducted. This paper presents the methods used to assess the acoustical performance both before and after installation of retrofit acoustical materials that did not significantly alter the visual aesthetics of the classroom as was required.

## 2 Method

As part of the assessment, measurements and room acoustics modelling was performed using Odeon ray-tracing acoustical software both before and after retrofit construction.

### 2.1 Initial visit

During an initial visit, the classroom was observed to be constructed from hard-tiled and stone walls, exterior and extensive interior glazing, epoxy concrete floors, and a gypsum board ceiling (see Fig. 1).

### 2.2 Pre-retrofit modelling and measurements

To assess the acoustical conditions of the original classroom, impulse response measurements were performed at several locations using the swept-sine approach as built into Odeon. A Trimble SketchUp model of the room was created by AcoustiGuard to define its geometry, which was then imported into Odeon. Based on visual observations of room finishes, estimates for absorption coefficients were assigned in Odeon to the room's surfaces using the built-in material database.

A comparison of the predicted and measured room acoustical parameters was made for each measurement location. To improve the accuracy of the model, it was calibrated to the measurements using the Genetic Algorithm (GA) built into Odeon. This procedure allows the user to define a potential range in octave bands for each material's absorption coefficients. The GA iteratively changes the material properties and recalculates the model until a better match with the measured parameters is achieved. The GA is essentially a search algorithm that works well with multi-dimensional problems and converges to the most optimum solution [1].

### 2.3 Retrofit design and construction

Based on the calibrated Odeon model, specific retrofit acoustical materials were evaluated based on manufacturer's absorption data. To preserve the aesthetics of the room, material selections were specifically limited to (1) options without exposed fibres, and (2) transparency, such as transparent Micro-Slotted Panels (MSP) [2] and Perforated Gypsum Board (PGB) ceilings with fibre backing [3].

The MSP were installed to partially cover the windows, wall tiles, and interior glazed walls while the ceiling was entirely converted to PGB with 2" of mineral fibre above only the perimeter of the ceiling. The look of the room was essentially maintained after the retrofit installation, as can be seen by comparison between Fig. 1 and Fig. 2.

**Figure 1**: Original classroom

**Figure 2**: Retrofit classroom

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## 2.4 Post-retrofit modelling and measurements

Once the retrofit materials were installed, additional acoustical measurements were performed following the same procedure as the initial measurements.

For the retrofit model, a comparison of the predicted and measured room acoustical parameters was made. The GA was again used to calibrate the room acoustics model to the measurements.

# 3 Results

The average reverberation time (T20) measurement (of 15 measurement points and two source positions) and the prediction results for the original and retrofit room, both before and after calibration, are plotted in the figures below.

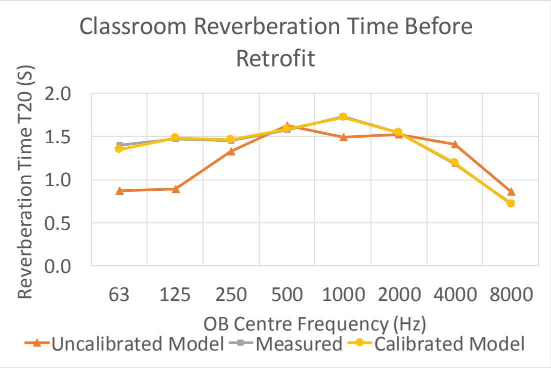

**Figure 3:** Pre-retrofit results

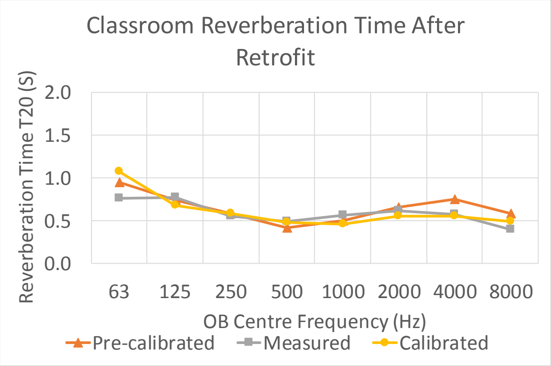

**Figure 4:** Post-retrofit results

# 4 Discussion

The results show that the retrofit materials significantly reduced the mid-frequency reverberation time within the classroom from an average 1.6 s to 0.6 s. This reduction also resulted in a substantive improvement in speech intelligibility from STIPA 0.44 “Poor” to 0.64 “Fair”.

From Figure 3, for the pre-retrofit case, the reverberation time of the initial un-calibrated model had significant error in the 63 Hz and 125 Hz bands and noticeable error between 250 Hz and 8000 Hz. However, after calibration, the modelled reverberation time almost exactly matches the measured reverberation time with no noticeable error. This result should be expected since the initial un-calibrated model was based entirely on estimates of surface absorption coefficients. It is surprising that the un-calibrated results are mostly lower than the calibrated results since it is known that current methods of evaluating material absorption typically under-estimate actual absorption. This could be due to inaccurate assumptions about the cavities behind the existing surfaces. At higher frequencies, the expected trend was observed. It is encouraging that after calibration the results match the measurements indicating that the calibration is a worthwhile procedure.

From Figure 4, for the post-retrofit case, the calibration was seen to have less of an effect since the base model was already calibrated. This also suggests that the material properties provided by the material suppliers were reasonably accurate except at the highest frequencies where actual absorption was slightly higher as expected. There was some noticeable remaining error at 63 Hz likely caused by constraints placed upon the GA during the calibration process that prevented it from adjusting material absorption coefficients outside of a defined range.

# 5 Conclusion

A classroom with poor acoustics and low levels of speech intelligibility was studied as part of installing retrofit acoustical materials. Based on initial in-situ material guesses and impulse response measurements, a room acoustics model was created and calibrated using Odeon ray-tracing acoustical prediction software and its built-in Genetic Algorithm. The calibration significantly reduced prediction error of the pre-retrofit model compared to measurements. This is because all the material properties of the pre-retrofit model were estimated by matching materials from the Odeon database based on visual observations in the room. The post-retrofit model still benefited from calibration, but since it was based on the calibrated pre-retrofit model most of the material properties were already calibrated. Without a calibrated pre-retrofit model, it should be expected that there would have been larger errors in the post-retrofit prediction. This demonstrates that calibration of ray-tracing models is a worthwhile exercise when accurate predictions are required for selecting retrofit materials. Without calibration, there may be noticeable error in the prediction results.

# Acknowledgments

Thanks to Peter Harper, Architectural Acoustics Manager Acoustiguard-Wilrep Ltd. for commissioning our involvement in this project and providing the opportunity to perform the modelling and measurements.

# References

[1] Christensen, C. L., Koutsouris, G., Rindel, J. H. Estimating absorption of materials to match room model against existing room using genetic algorithm. *Proceedings of Forum Acusticum, Krakow*, 2014.

[2] DeAmp Panels: https://goo.gl/3vviTP

[3] Knauf Danoline Perforated Drywall: https://goo.gl/eF1Fpp

# PRACTICAL CONSIDERATIONS OF ONTARIO'S TARION BUILDER BULLETIN 19 ACOUSTICAL REVIEWS FOR NEW CONDOMINIUM BUILDINGS

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## 1 Introduction

Under the Ontario New Home Warranties Act Plan, all new condominium projects must be registered with the Tarion Warranty Corporation under the Builder Bulletin 19 (B19) program. The program is intended to ensure building design and construction meet required standards to protect both the buyer and Tarion as the warranty holder. Apart from the legal requirements of meeting Ontario Building Code (OBC), B19 certification further requires that design and construction meet good architectural and engineering practice in specific risk areas outlined by Tarion.

Acoustics are included in the B19 risk areas with sound transmission and mechanical sound/vibration being major areas of concern. Successfully implementing these acoustical requirements for condominium projects involves careful coordination with the entire design team and the builder. Even with recent updates to the B19 documents that highlight acoustics as a separate risk area, these items still remain an afterthought for many architects, developers and builders.

In this paper, we discuss some of the challenges raised by the B19 process for the acoustical consultant during the design process including ambiguity in the design requirements and acoustical approvals. Common areas of concern identified during the design reviews and typical solutions for resolving issues which satisfy both the owner and the acoustical consultant are also presented.

The B19 process also involves field reviews and proof of performance tests to confirm the design requirements have been adhered to. We present prevalent issues which are identified during field review site visits, the consequences of these deficiencies in as-built configurations, and proven remedial approaches where non-compliance is found.

## 2 Design criteria discussion

### 2.1 Building performance

Acoustical requirements for the Ontario Building Code (OBC) and National Building Code of Canada (NBCC) are only provided for sound isolation and only then for STC ratings for demising walls between suites and other suites, corridors, common areas, and garbage chutes.

The B19 program expands the acoustical design requirements through the newly updated Risk Area 11 – Acoustics [1] to include sound transmission between suites and other common areas, mechanical sound and vibration transmission, and electrical components such as generators and transformer noise which can affect other units in the same building, or off-site receptors / residences.

The B19 program only identifies these as "Risk Areas" without imposing specific criteria or constraints on their evaluation. Responsibility for establishing criteria, defining and meeting best practices, and implementing appropriate design solutions for these areas rests with the acoustical consultant who has increased control of the overall acoustical design of the project, but also has increased liability for any potential issues that arise.

### 2.2 Environmental noise

A consideration often overlooked during the design process are the impacts of noise generated by the building on the building itself. These issues are typically addressed as environmental noise concerns during site plan approval by generalized statements and reviews since the full mechanical systems have not been designed / selected at that stage. However, if not addressed in the building design, mechanical plant – (e.g., HVAC plant, emergency generators) self-contamination can impact residential units within the development. This can be especially prevalent when separate consultants are retained for SPA and for B19. In either case, environmental noise is a critical design consideration which must be included in all B19 reviews.

## 3 Common design oversights

Key commonly overlooked design aspects within some of the broadly defined B19 acoustical risk areas are discussed in the following sections.

### 3.1 Sound isolation

- **Adjacency and space planning** – Careful space planning during early design to promote compatible space usages greatly reduces the need for acoustical controls.
- **Partition caulking** – Acoustical caulking details at partition joints (e.g., wall /floor) should be shown on design drawings and acceptable products included in project specifications.
- **Penetrations** – All penetrations need to be fully sleeved and sealed in all acoustically rated walls.
- **Value engineering** – Cut backs to marginally meet acoustical design criteria especially in critical areas do not allow for normal construction deficiencies, resulting in poor performance.
- **Substitutions** – (e.g. structural studs vs 25 ga. studs).

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### 3.2 Mechanical services

- **Vibration isolation** – OEM isolation does not consider floor spans, contiguous space sensitivities and is often insufficient.
- **Sanitary stacks** – Horizontal pipe runs can be very disruptive. Cast iron stacks should be used wherever possible. Horizontal runs should be acoustically lagged or fully enclosed in acoustically rated bulkheads.
- **Garage doors** – Rigid mounting of motors and rails generate structure-borne noise to structurally coupled suites.

### 3.3 Amenity spaces and retail

- **Unique amenities –** Golf simulators, squash courts, and movie rooms all have specific unique challenges ideally addressed through separation from suites and space-planning.
- **Retail tenants –** Acoustic controls depend on anticipated retail tenants. A high STC base construction with tenant covenants for additional acoustic controls is often a sufficient approach.

## 4 In-situ construction reviews

Field reviews during various stages of construction identify potential issues and corrective action before issues promulgate through the entire building. The first reviews occur at the first completion of key elements (e.g., when drywall boarding occurs at the lowest floors of a high-rise), when the most critical acoustical items have not yet been fully completed and can be reviewed at an early stage. Typical issues identified in construction reviews include:

- Incorrect application / lack of acoustical caulking
- Sanitary runs in contact with bulkheads and ceilings
- Debris in gap between garbage chutes and slab
- Tie holes in concrete construction not filled
- Acoustical ceilings rigidly connected to perimeter walls

## 5 Proof of performance testing

The final role of the acoustical consultant in the B19 process is to conduct proof of performance testing to verify as-built performance of the building meets OBC requirements and the intended level of acoustical performance of the design.

### 5.1 Acceptable performance levels

The 2015 edition of the National Building Code of Canada (NBCC) [2] proposes changing the sound isolation rating between residential suites from a minimum STC 50 for the wall or floor/ceiling assembly to a minimum ASTC 47 value. This change from a design based criteria to a performance based criterion places more emphasis on the proof-of-performance testing by the acoustical consultant. The 3-point difference between laboratory and apparent performance is in line with typical field ratings observed by Novus in hundreds of STC tests and indicates good construction practices were used. It is anticipated that this requirement will be adopted by the OBC and has been applied as the absolute minimum acceptable field performance criteria in B19 projects.

### 5.2 Field deficiency mitigation

When proof-of-performance testing indicates an assembly has not met the minimum field requirements mitigation is required prior to sign-off from the acoustical engineer. While it is often simple to identify the root cause of the acoustical deficiency (poor detailing, omitted elements, incorrect installations) the critical step is to develop a mitigation solution which is cost effective, simple to implement, and most importantly provides the required level of acoustical performance. A selection of unique mitigation solutions successfully implemented in projects is provided below.

**Case 1:** Resilient channel was omitted from the ceiling construction in wooden floor joist separation of stacked townhomes.

**Solution:** As shown in Figure 1, instead of removing the entire GWB ceiling to install the channel, holes were cut in the drywall to allow air movement. Resilient channel was then installed over the existing layers and a new drywall ceiling was added. Performance tests showed expected ASTC levels for the base configuration were met.

**Case 2:** Draining the kitchen sink was a unit was clearly audible throughout the entire living room of the unit below.

**Solution:** Investigation on-site found gypcrete poured above spilled into the bulked head below, rigidly connecting the PVC sanitary stack with the living room bulkhead as shown in Figure 2. This acted as a large plate radiator, with every drop amplified for the tenants below.

**Figure 1:** RC channel installed with holes for air

**Figure 2:** Gypcrete rigidly tying stack to bulkhead

## References

[1] Builder Bulletin 19R - Condominium Projects, Design and Field Review Reporting: Tarion Warranty Corporation, 2016.

[2] Quirt, D. and Zeitler, B. (2014) *A New Approach To Building Acoustics Regulation In Canada*, Canadian Acoustics, Vol. 42, No.3.

# THE CONDOMINIUM PROCESS AND NOISE

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## 1 Introduction

In our practice, we frequently provide acoustical engineering services to condominium developers and other builders of multi-unit residential construction. Some are large local firms, others are small with limited experience.

In all cases, we find that it helps to break down the project process into individual steps and activities, with clear identification as to who is responsible for what. All participants, including the owner (or future owner) down to the General Contractor's labourer who watches over the site, have a role to play.

This paper presents a flow chart and description of the process we use: Project Definition; Concept Design; Detail Design; Tender and Construction; Commissioning; and Final Reporting. In Ontario, we have the Tarion Home Warranty Program [1] which superimposes accountability standards and reporting requirements for some types of projects.

This process can be applied to large and small projects, high end developments to social housing, as well as wood, steel or concrete construction.

## 2 Project process

### 2.1 Project definition

This step establishes Design Parameters consistent with client expectations and costs.

New clients typically do not have a clear understanding of acoustic design criteria, describing their expectations as “sound-proof”, “inaudible”, and other terms that are neither realistic nor affordable. We start our projects with the preparation of an Acoustic Design Brief which articulates all acoustical performance criteria in clear and measurable terms. These include those listed in the Building Code (STC and IIC), as well as a host of other criteria, including:

- Control of environmental noise (traffic and stationary sources as applicable) as is regulated by the Municipality [2] based on authority delegated by the Province [3].
- Base-building external noise emissions (to ensure compliance with the City of Ottawa Noise Bylaw [4]) and self-noise objectives for outdoor spaces, sources including A/C condenser units, heat pumps, exhaust fans and more.
- Noise within the units due to HVAC equipment within the unit (compliant with the Guidelines published by ASHRAE [5]), including noise from exhaust fans in kitchens, washrooms, dryer exhausts, and hot tubs/whirlpools.
- Control of noise from special issues such as garage door openers or garbage room roll-up doors.
- Vibration isolation of the base-building machinery and equipment (pumps, air handling units, cooling equipment, etc.).

Working with the Developer and Architects, initial cost-estimates can be developed (“Class D” [6]). As the Developer learns more about the cost implications of what is being asked for, the above design criteria can be modified.

### 2.2 Concept design

Early in the design process, it is required to submit an Application for Site Plan Control to the municipal authorities for review and approval. While only a plan drawing at grade, it is required to define the planned buildings in enough detail that the application can be fully understood: building footprints and number of floors.

Once the concept designs have been developed to a point suitable for review, these can be subjected to cost-estimates offering a higher level of precision and thus a better degree of confidence (“Class C”).

### 2.3 Detail design

Once a concept design has been identified as the preferred option, this can then be matured to a complete design, suitable for tender and construction. Sometimes this is broken down into several sub-parts, but often, especially with a mature design team and motivation to work fast, a “one-pass” approach is adopted.

Our contributions to this phase include providing input to the Architect as needed for any unique conditions, and provision of a set of Acoustical Notes. If the project includes a set of specifications, we provide input to these. Often these will be in NMS [7] format but not always.

The detail design, once completed, allows for the further refinement of cost estimates (“Class B”). Should any excesses over budget be identified, there may still be time to revise the original design criteria, before any money actually gets spent.

In the context of for-profit housing, at some point during the above process, the product needs to be presented in the marketplace so that purchasers can make deposits and target move-in dates. Once this milestone has been reached, it becomes much more difficult to change the detail design, as once commitments have been made, it is difficult-to-impossible to revise them without engendering dissatisfaction.

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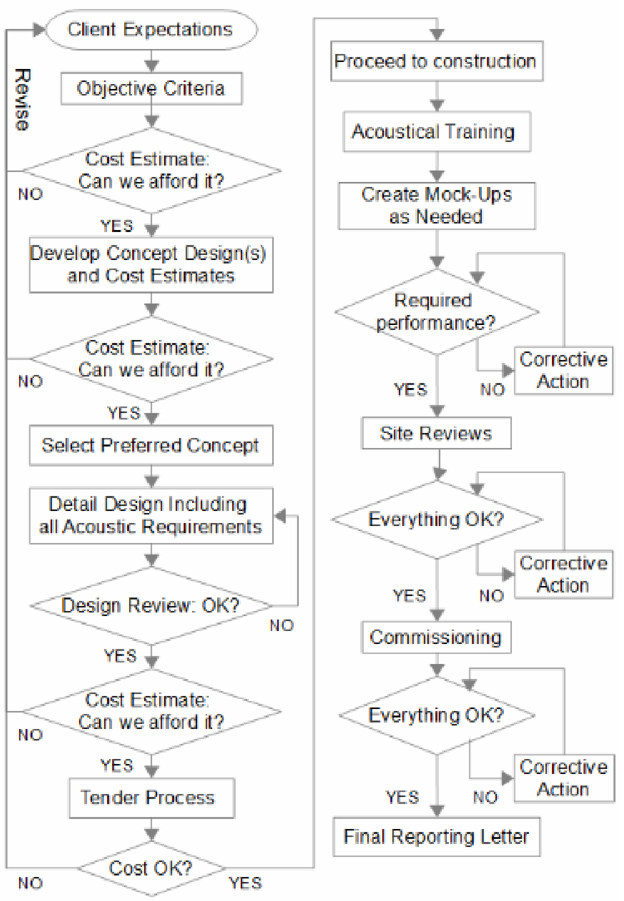

**Figure 1:** Flow chart of the condominium process

## 2.4 Tender and construction

For new clients/projects, we offer acoustical training for the Site Supervisor(s) and sub-trades. This takes roughly an hour, and secures names and signatures from each of the key contractors working on the project. We've found this very effective for reducing the incidence of construction issues later, and at the very least, it increases accountability should any issues arise.

During construction we undertake site reviews of the work-in-progress, visiting the site at least for the following milestones: post-demolition (if the project is the conversion of an existing building), so as to identify any hidden details requiring a Site Instruction; post completion of the framing, early in the prep-work phase, well before anything gets covered over; when mechanical and electrical rough-ins are progressing; key wall junctions as they are developing and completed; and installation of the floating floors (if applicable).

Of note, while this paper has presented the above process from the perspective of design and construction of for-profit condominiums, on a practical level, we adopt the same approach for our non-profit, affordable housing projects as well. For these projects, we are typically asked to spend additional time on value engineering during the design process, to identify cost-savings.

## 2.5 Commissioning

For the construction of new condominiums, we are required to follow the requirements of Tarion Builder Bulletin 19R. This includes testing of the final noise isolation performance of a sample of units. We do this following the requirements of ASTM E336 [8] and E1007 [9].

Depending on the project, our commissioning can extend to verification of noise levels due to HVAC and other equipment, both internal and external to the building.

Should any issues arise, these can then be addressed. However, we emphasize to our clients that commissioning is not the best time to identify and fix weaknesses, but rather, the process outlined above is intended to avoid issues at commissioning and beyond.

Depending on the project, sometimes we do very little testing to verify that the intended field performance has been achieved. It is the threat of testing that keeps the trades on task, combined with frequent site reviews.

## 2.6 Final reporting

We usually end our projects with a short reporting letter outlining our key activities, and then attaching a sample of the results of our testing (essential for projects subject to the requirements of Tarion Builder Bulletin 19R).

## References

[1] Tarion Builder Bulletin 19R, published December 2016, effective in January 2017.

[2] City of Ottawa Environmental Noise Control Guidelines (ENCG), 2016.

[3] Ontario Ministry of the Environment NPC-300 published August 2013.

[4] City of Ottawa Noise Bylaw, 2017 review.

[5] ASHRAE HVAC Applications Handbook Chapter 48, 2015.

[6] Cost-estimate Classes as defined by PWGSC: https://www.tpsgc-pwgsc.gc.ca/biens-property/sngp-npms/bi-rp/conn-know/couts-cost/definition-eng.html

[7] National Master Specification (NMS) from PWGSC.

[8] ASTM E-336 Standard Test Method for Measurement of Airborne Sound Attenuation between Rooms in Buildings (current revision).

[9] ASTM E-1007 Standard Test Method for Field Measurement of Tapping Machine Impact Sound Transmission Through Floor-Ceiling Assemblies and Associated Support Structures (current revision).

# BEAVER BARRACKS ACOUSTICAL ENGINEERING CASE STUDY

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## 1 Introduction

This paper presents a case study of the acoustical engineering undertaken in support of a 252 unit affordable housing project. It was located in an area just south of the Ottawa downtown core, known as the "Beaver Barracks" (so-named for the past use of the site as temporary housing for troops during the Second World War).

The project started with a competitive bidding process. We partnered with the successful proponent, Centretown Citizens Ottawa Corporation (CCOC), with which we had/have an ongoing working relationship. High levels of cooperation between the Owners, Project Architect, Mechanical and Electrical Engineers, and the General Contractor meant that good acoustical performance was delivered in a timely and cost-effective manner.

This paper describes the project process from concept to final commissioning, including design criteria, concept designs, environmental (traffic) noise, field reviews and testing. Many challenges arose during the project: complications due to the mechanical system sophistication (district heating with energy recovery); quality control issues with some sub-trades; and the complexities of three different building types (concrete apartments; wood apartments, and stacked wood townhouses); all located on a small site surrounded by buildings and roadways.

While nothing was particularly extreme in terms of acoustical design, the project in its entirety is an excellent example of the processes and interactions necessary to achieve the intended acoustical outcomes, including the twists and turns that emerged along the way.

## 2 Background and overview

The City of Ottawa has a large backlog of individuals on the waiting list for social housing. This need is especially acute in the downtown core where there are limited opportunities for new construction.

This project made use of a vacant block of land just north of the 417 highway, at the base of Metcalfe Street. Many social services are available within walking distance including the YMCA next door. Contributions came from all levels of government, and some private sector money as well, for a total project cost of $65 M.

The project included five different buildings, of three different types: two 8-9 storey concrete apartments at the south of the site facing the highway, a four storey wood apartment along the north side of the site, and two blocks of stacked townhouses to the west and east sides of the site, leaving an open courtyard at the center for the new community garden and other recreational usage. Almost all parking is underground. The ground floor levels of the concrete apartments include some commercial space as well. A variety of units were built, ranging from bachelors to three bedrooms.

Some general complications included budget pressures, an existing ambulance station on the site with the need for its function to be maintained during the project, and the design oversight by the National Capital Commission.

## 3 Project process

### 3.1 Development and design

The distinguished Ottawa-based Architectural practice of Hobin Architecture was the lead design authority for the entire project. Its wide portfolio and our long-standing prior-existing working relationship meant that our inputs to the design process were limited to a few drawing reviews and some value engineering.

Early in the design process, a sustainability Charrette was held. This two day event provided opportunities for many stakeholders to have input, including BUGS, the Bytown Urban Garden Society which occupied a small community garden on the site. This was a meaningful activity, which resulted in the support of all concerned parties. It also allowed for the consultant team to make revisions to the Site Plan in order to significantly reduce propagation of highway traffic noise on to the site, using the two concrete towers as barriers.

The following acoustical criteria were adopted for the project: City of Ottawa's Environmental Noise Control Guidelines (i.e. prediction and mitigation of traffic noise per MoE requirements [1]), STC 55-57, IIC 55, ASHRAE guidelines for noise levels in occupied spaces due to mechanical systems [2], and the control of plumbing noise following CMHC guidelines [3]. These and other details were collated in an Acoustic Design Brief that was circulated to all design authorities and Centretown Citizens Ottawa Corporation (CCOC) for ongoing reference.

During the detail design process we provided input concerning noise and acoustics, as well as identifying cost saving opportunities. One that was particularly noteworthy was a substantial reduction of the number of vertical plumbing stacks. This was done by putting single stacks within the party walls to serve two adjacent units, rather than double stacks with one on each side of the party wall. This also simplified the construction and added more floor space to the small units.

While the traffic noise study made with Stamson [4] indicated levels above the exposure limits for standard windows, the need for special acoustic windows was

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avoided. The original design was for windows with 6mm glazing on both panes, which was accepted as being more than adequate to ensure indoor noise levels were compliant.

For impact noise isolation, the wood buildings used a pre-manufactured product called Sonodeck by InsulFloor. In the concrete apartments, an engineered floor system was used with a modest impact isolation membrane below.

Some complications did however arise in the design process. Following a design review, the NCC directed that the south-facade of the concrete apartment buildings should have balconies, facing the highway. This would have added significant complexity and cost to the project, and the idea was rejected as it would increase the amount of traffic noise entering the apartments.

The manufacturer for the energy recovery ventilation (ERV) unit was changed for the second concrete appartment. This caused concerns for noise. We assisted the Mechanical Engineers with ASHRAE-based modeling [2] and confirmed that our design criteria would be achieved.

### 3.2 Construction

The construction was phased, so as to permit the use of the space on the site for all related staging. The first concrete apartment was built, which included a new ambulance station. This was then occupied, so that the prior-existing stand-alone ambulance station could be demolished to make way for the second concrete apartment. The third building to be built was the wood apartment to the north of the site, followed by the two blocks of stacked townhouses.

The prior-existing relationships between CCOC, the Architects, General Contractor and ourselves meant that we had a high degree of trust and confidence in each other's capabilities. The General Contractor also provided excellent Site Superintendents and First Lieutenants. Good continuity was maintained throughout the build, nearing two years.

Some complications for noise on this project came from the fact that the site was always busy and had many trades working on various aspects of the project. There were also entirely different crews working on each of the building types (wood versus concrete), which lowered consistency.

Complications also arose from the ducting required for the ERV system, with small fire-dampers for every unit. The site conditions made the ceiling-level bulkheads very tight and there were difficulties installing all of the needed duct work. Working with the City Authorities, Mechanical Engineers and General Contractor, we were able to delete some of the ducting and simply use the space enclosed by the bulkheads themselves as the duct for air transfer.

The new seismic requirements of the 2006 revision to the Ontario Building Code [5] proved to be an added challenge: sheet wood was required to be installed on both sides of the party walls in the wood apartment as it was being erected. This added the obvious conflict of the timing of insulation into the wall cavities before the roof went on. The City Building Permit Inspection Authorities insisted upon this, citing concerns of an earthquake during construction (which in fact did happen).

Vibration isolation of the heat pumps was also a concern, and a mock-up using rubber isolation pads was created in one apartment and verified.

Over the course of the project (2008-2012), we undertook 35 site inspections, sometimes visiting the site weekly. The drywall contractor was previously known to us from a condo project which had significant quality control issues. Our frequent site reviews, fully funded on an hours-worked basis by CCOC, most certainly had a positive benefit on the overall noise isolation performance achieved.

### 3.3 Commisionning and follow-up

Throughout the build we made frequent strong overtures to the drywall contractor and others, that there would be extensive testing of the final work and any defects identified would need to be corrected at no cost to CCOC or the General Contractor. In the end, very little testing was done.

Sound leaks were identified from the ambulance station to the apartments above. This was due to piping penetrations through the slabs. The ambulance station has a loud paging system which exacerbated the issue.

Concerns were expressed by some residents in the wood apartment about excessive low frequency noise and perceptible vibration. This was caused by a pump in the basement of the building, which was much louder than its companion. Repairs were made and the problem resolved.

There was some delamination in the laminate flooring of the wood apartment, that was originally attributed to issues related to the floating floor system below. It was later determined that the root cause was improper installation of the laminate flooring, aggravated by walking assist devices (wheelchairs and walkers).

## 4 Conclusion

This project demonstrated that a collaborative approach between the project owners, architects, engineers, and general contractor, can result in achieving the intended levels of acoustical performance.

## Acknowledgments

I am appreciative of the contributions and review comments provided by Mr. Graeme Hussey, of Centretown Citizens Ottawa Corporation, the owners of the project.

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# HERITAGE BUILDING CONVERSIONS AND ACOUSTICS

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## 1 Introduction

The City of Ottawa has many heritage-designated buildings that have reached or passed the end of service life for their most recent usage. This includes old schools and institutional and commercial buildings.

This paper will present four case studies of conversions to residential (condominium) usage. Each project is unique, and most include assemblies that are not in the available test data. Challenges encountered included original as-built deficiencies, subsequently-introduced defects, major seismic weaknesses, and demanding architectural expectations.

Project one was an old, nine room school building, with high ceilings. Each classroom was cut in half to make two units, each fitted with sleeping lofts.

Project two was an old warehouse building that at one point in its history had heavy machinery within, with substantially enhanced wood floor structure. The combination of an ambitious architectural plan and many site conditions uncovered in demolition made this a very interesting project.

Project three was a small site in the Byward Market, with old sheds, garages and a couple of century-old wood houses.

Project four was also a school building, reworked with an ambitious plan for luxury condominiums. Post demolition of the old interior, many weaknesses were found in the masonry detailing, and substantial enhancements were required for seismic.

## 2 Project 1: École St-Charles

This century-old school building had reached the end of its useful life, and was abandoned. The flat roof was compromised and water had entered the building, soaking much of the interior, and creating habitat for mold and pigeons.

This was the first project of its type for the Developer (also acting as the General Contractor), and so there was a steep learning curve. However, the Architect and construction management team were experienced and savvy, and were able to adapt and respond quickly to emerging issues.

The classrooms had high ceilings, making them suitable for the addition of a sleeping loft above the kitchen. From an acoustical perspective, the challenge was to implement the new work at the same time as correcting prior-existing issues. Many holes had been made through the old building, and the moisture penetration had rotted some of the wood, some of which was only identified post-demolition with a section of floor collapsing.

Following demolition of the old interior finishes and removal of waste and mold, new party walls were framed as single studs. In hindsight, these would have been better as staggered or double stud walls, as the base building demising walls had higher ratings. Post-demolition sound testing would have identified this potential, but on a practical level, the design had already been completed.

The original stair wells were retained. However, these were profoundly squeaky and subjected to thousands of screws and plywood overlay.

Some issues arose with the lack of familiarity of the developer's sub-trades with the standards needed for the work. As an example, the floating floors were installed snug to the walls. After a weekend with the building closed up tight and humid, they all swelled, creating waves in the finished flooring. Fortunately, with some open windows and dehumidifiers, things settled back down.

The complexities of meeting City of Ottawa Heritage requirements were not initially fully appreciated (the building exterior had to be repaired to look the same, windows and masonry), adding time and cost to the project.

Commissioning was originally scheduled for a weekday evening, however noise disturbance through the windows to an adjacent residence meant that the testing had to be deferred to the daytime, the following weekend.

## 3 Project 2: 95 Beech Street

This building had very high levels of structural stiffness and noise isolation from the base building. It included 14 by 3 inch floor joists at 9 inch centers and 2 inch tongue and groove pine sub-floors which were well nailed with heritage nails.

The architectural plan included many challenging features for noise. One of those was having exposed masonry on as many interior walls as possible (exterior insulation and finish system for thermal and moisture control was applied to the outside). This created significant challenges for party wall/external wall junctions, as well as a serious impediment to the ongoing interior fit-up: the sandblasting of the internal walls to clean them had to be repeated several times, leaving a mess to be cleaned up. Another architectural issue for noise was leaving many of the original large wood beams exposed. The suite layouts all included walls at 45 degrees, further challenging the trades.

The desire to provide many features to the purchasers made the build much more complicated. This included central air conditioning for each unit (all condenser units were located on the roof) and gas fireplaces which were challenging to vent. Exacerbating the situation were many

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late changes requested by purchasers, which in hindsight should have been declined or priced more aggressively.

Many upgrades were required to meet seismic requirements. This only became fully clear once the demolition of the prior-existing interior was completed and the remaining base-building exposed to the structural engineer. Many custom made steel pieces were fabricated and installed, adding costs and delays.

The original plan had been to retain the prior-existing hardwood floors, which were clear of any knots (!). However, when the floor in the model suite was sanded and the planks were no longer glued together by many layers of finish, the squeaks were so loud as to interfere with sales during the open house. All existing hardwood was removed, and the prior-existing sub-floor thoroughly screwed. On the positive side, this allowed for the incorporation of a floating floor system under the new hardwood.

All interior framing was done in metal, the expectation being that this would be more amenable to the complicated floor layouts. However, the protracted construction interval and early rush to get the framing in lead to significant damage of the new framing and many repairs were required before it was all closed in.

Ongoing issues with the workmanship of acoustical caulking were resolved with the assignment of a young person to this task for several months.

## 4 Project 3: Montmartre

This project was located on a small site in the Byward Market, with old sheds, garages and several century-old wood buildings. The City of Ottawa was most adamant that the two houses and old commercial building be retained. In hindsight, almost none of the original materials remain visible and the extra work to retain them seems rather pointless. The old garages were demolished, and a new concrete apartment building notched in to the site, also providing parking below grade. A new wood building was added, configured as stacked townhouses.

The design intent was to provide an STC rating in the high fifties, and design for IIC 55.

As a result of the small size of the site, the buildings were done progressively, with the heritage structures reworked first. Following the completion of these, the concrete apartments were built, providing further revenues as they were occupied. Finally, the wood stacked townhouses were built.

This was the first project of its type for the developer and General Contractor. It in fact combined different projects using different trades for each type due to the different building types (wood and concrete). For this reason, some major issues with construction quality control arose:

- problems with GWB fasteners and resilient channels;
- gaps in insulation covered-over by GWB;
- missing insulation for drain noise control;
- wood furring substituted for resilient channels on a party floor/ceiling.

Another unanticipated complication was that the outdoor patio spaces above other occupied spaces caused disturbance. This required some disasessmbly and rework with vibration isolation components and better load distribution into primary structure.

In hindsight, we agreed with the Developer that more site inspections would have been useful, rather than the after-the-fact approach of responding to complaints and undertaking extensive testing and subsequent rework of defective areas.

Post-occupancy, noise in the corridors due to loud tenants and visitors was identified as an issue, however, this was not within our scope of control as the acoustical engineers.

## 5 Project 4: 19 Melrose

This building was much like the other school building discussed above: basically abandoned with the pigeons taking over. While the original architectural plan was to retain some of the interior finishes, it was not feasible on a practical level. This was due to the extensive work required on the base-building, prior to the starting of the new fit-up.

Once exposed, the interior brick work was far below acceptable standards, and it took many months for several masonry teams to re-point all of the mortar joints and make many other repairs. No other work could proceed until this was completed. It was asked if materials other than mortar could be used to fill holes (in order to save time and money). This was declined for noise as no relevant test data would be available.

Large gaps existed between the wood floors and perimeter walls at many locations.

Structurally, a considerable amount of retrofit steel work was required to meet the requirements of the Ontario Building Code. It was all custom, and all needed to be completed before the interior fit-up work could begin. These two issues added delays to the project, complicating things for the developer.

The new architectural design included removing some areas of existing floors, so as to take advantage of the large heritage windows. New balconies were added for some units.

A model unit was prepared, but not all of the acoustical detailing was compliant with the design. Resilient channels on a demising wall were inverted (open facing downwards), and the City Building Inspector insisted that it be reworked.

Post-occupancy, a complaint was raised about drumming noise coming through a bathroom wall, traced to a vibrating cell phone on the counter of the adjacent unit.

# COMPLYING WITH HIGH SOUND ISOLATION REQUIREMENTS IN ACOUSTICS STANDARDS WHEN A SUSPENDED CEILING EXTENDS CONTINUOUSLY OVER PARTIAL-HEIGHT INTERIOR PARTITIONS

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## 1 Introduction

In some buildings, sound isolation between rooms is important. For example, conversations between employees and their human resource professionals are meant to be private. Even when speech privacy is not a concern, sound transmitting between rooms can be annoying or distracting and can inhibit productivity, concentration or relaxation.

Acoustics requirements in building standards, guidelines and rating systems list sound transmission class (STC) most frequently as the sound isolation performance metric. STC requirements generally range between 40-50, with STC 45 being the most common[1]. Interior partitions are required to be full height from structural floor slab to structural floor slab with any penetrations sealed airtight.

Despite these requirements, some building designs have partitions that instead stop at the height of a suspended, acoustic ceiling, leaving an open plenum above. This may be due to the desired cost savings or a requirement to use premanufactured, demountable wall systems that can be relocated as space requirements change. The resulting open plenum above the ceiling creates a noise flanking path over the lower wall, resulting in noncompliance with the sound isolation requirements and occupant expectations.

This research studied how to achieve the required sound isolation ratings with plenum barriers above the partial-height partitions when the ceiling grid runs continuously over the tops of the partitions.

## 2 Method

A series of sound isolation tests was performed on a suspended, modular, acoustic ceiling system with and without various lightweight plenum barriers under laboratory conditions in a dual-room chamber. For the baseline test, the specimen comprised a metal suspension grid filled with ceiling panels, but no plenum barrier above the demising wall. Subsequent tests added various lightweight plenum barriers. In all cases, the ceiling grid ran continuously (uninterrupted) over the top of the laboratory's central demising wall.

### 2.1 Test facility and procedure

The tests were performed at NGC Testing Services in Buffalo, New York, in November and December 2016 by a Senior Test Engineer. The laboratory is accredited by the National Voluntary Laboratory Accreditation Program (NVLAP) (Laboratory Code 200291-0). Tests were performed according to ASTM E 1414 and E 413.

### 2.2 Ceiling system, components and installation

The ceiling panels were white, stone wool, measuring 1220 mm (48 inches) (nominal) in length by 610 mm (24 inches) (nominal) in width by 16 mm (5/8 inch) thick with square, lay-in edges. Their weight was 1.27 kg/m2 (0.26 psf). They have a noise reduction coefficient (NRC) per ASTM C 423 of NRC 0.75 and a ceiling attenuation class rating (CAC) of $\text{CAC}_{\text{panel}}$ 23 per ASTM E1414 and E413. The suspension system was a standard 24 mm (15/16 inch) wide, 38 mm (1-1/2 inches) high, steel, tee-bar suspension grid. The grid was installed in an uninterrupted manner, meaning the grid ran continuously over the central demising wall. For the baseline test, the ceiling panels ran continuously over the central demising wall.

### 2.3 Plenum barrier, components and installation

Prior phases of the research program determined that using lightweight, stone wool, insulation plenum barriers in combination with stone wool acoustic ceilings could achieve high $\text{CAC}_{\text{system}}$ ratings[2]. However, those tests were conducted with an interrupted grid configuration where the demising wall extended slightly above the ceiling, breaking the ceiling grid in two separate areas. The goal for this phase of the research was to test if stone wool plenum barriers could achieve similarly high sound isolation ratings if the grid instead ran continuously over the wall.

The material used for the plenum barriers was stone wool insulation with the following properties: thickness 38 mm (1-1/2 inches), density 128 kg/m3 (8.0 pcf), and surface weight 7.32 kg/m2 (1.5 psf). The plenum barrier boards had a fiber-reinforced, foil, facing on one side. Both single- and double-layer plenum barriers were tested. When the double-layer plenum barriers were tested, the foil was oriented towards the open ceiling plenum, not into the 41mm (1-5/8 inches) interstitial airspace between the two layers.

The plenum barriers were mechanically fastened along the top edge using common, self-tapping, sheet metal screws with insulation washers into a common 41 mm (1-5/8 inches) wide metal channel that was attached to the test chamber overhead slab. Screws were spaced approximately 305 mm (12 inches) to 457 mm (18 inches) on center.

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Typically each 610 mm (24 inch) panel had two screws along the top. The bottoms of the plenum barriers were only friction-fitted against the top track of the demising wall and the grid. They were not mechanically fastened, glued or caulked.

Each panel was abutted to the adjacent panels along the sides with no overlap. The vertical seams between adjacent panels were taped using 50 mm (2 inch) wide metal tape for sealing butt-joints. When the double-layer plenum barrier was tested, the 610 mm (24 inch) wide panels were staggered 305 mm (12 inches) so that the seams were not aligned. This required a small cut along the bottom of one layer of the plenum barrier boards so that they could slide down over the grid bulb and allow the bottom of the plenum barrier board to sit on the top track of the demising wall. No caulk or sealant was used. Small gaps around and in between some of the plenum barrier panels were visible. Most gaps were closed during installation due to the pliability of the stone wool. The panels were cut slightly oversized and then compressed vertically and laterally during installation, which helped prevent gaps.

The ceiling panels were installed last. They did not extend under the plenum barriers. This is an important factor in achieving the high sound isolation ratings.

## 3 Results

The effect of installing the single- and double-layer stone wool plenum barriers with a continuous grid configuration on normalized transmission loss ($D_{n,c}$) and $CAC_{system}$ values are shown in Figure 1 relative to the baseline test of the ceiling alone without any plenum barrier.

## 4 Discussion

The Optimized Acoustics Research Program is an ongoing, multi-year, multi-organization investigation into cost-effective means of designing and constructing interior architecture that complies with the acoustic requirements in industry standards, guidelines and building rating systems. It began in 2014, and progress updates of the findings have been presented at and published in the proceedings of InterNoise 2015, NoiseCon 2016, NoiseCon 2017 and Acoustics Week Canada 2015 and 2016 as well as published in various industry magazines and journals such as Sound & Vibration, Canadian Acoustics and Construction Canada. To learn more about the findings of other research phases or more details about this phase of the research, refer to one of the whitepapers or articles in the above listed sources or go to www.OptimizedAcoustics.com.

Other findings of this phase of the research include the importance of the foil facing on the plenum barrier board. When removed, the $CAC_{system}$ rating decreased seven points for a single-layer plenum barrier and ten points for a double-layer plenum barrier. Conversely, whether or not the vertical seams between abutted plenum barrier boards were taped did not affect the CAC rating of the system.

## 5 Conclusion

Historically, it has been believed that installing an acoustic ceiling continuously above partial-height interior partitions leads automatically to poor acoustic performance and noncompliance with user expectations and standards. The findings shown in Figure 1 demonstrate that it is possible to achieve high levels of sound isolation, $CAC_{system}$ 40-52, between rooms by using common, stone wool, acoustic ceilings combined with plenum barriers, even when the suspended, modular, ceiling grid runs continuously above the partial-height interior partitions. The design approach and installation method defined in this research can lead to compliance with the acoustic standards, guidelines and building rating systems that require STC 40, 45 and 50 levels of isolation. These findings can be used by designers and building owners to optimize acoustic performance when a continuous ceiling is desired but full height walls are not.

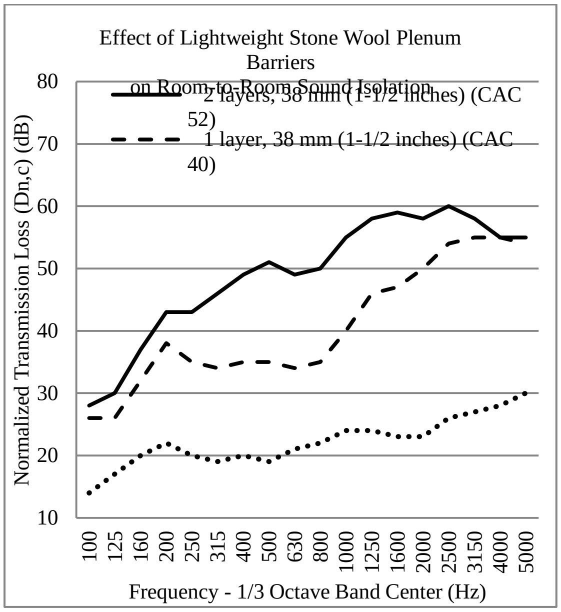

**Figure 1:** The effects of using lightweight, stone wool, plenum barriers on room-to-room sound isolation when the interior partitions stop at the underside of a continuous, suspended, acoustic ceiling.

## Acknowledgments

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# CASE STUDIES: EFFECT OF FASTENERS BRIDGING RESILIENT CHANNELS ON AIIC PERFORMANCE IN WOOD-FRAMED CONDOMINIUMS

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## 1 Introduction

This paper presents two case studies of wood-framed condominium projects where complaints were raised by occupants/owners within the first year of occupancy. The complaints were consistent with low insulation of impact sounds across floor-ceilings – footfalls from the units above were said to be intrusive within the units below.

Apparent Impact Insulation Class (AIIC) measurements, as well as inspection of the floor-ceiling construction with ceiling drywall removed, were completed within several units. It was confirmed that many drywall fasteners penetrated floor joists, thus bridging resilient channels and negating their proper function.

For both projects discussed in this paper, a strong correlation was found between the percentage of resilient channel / floor joist intersections with bridging fasteners, and the AIIC score.

## 2 Background information

Impact Insulation Class (IIC) is a single-number rating system that describes the insulation of sounds due to impacts on the top side of a floor-ceiling assembly within the space below. A greater IIC value indicates better insulation of impact sounds. The Ontario Building Code recommends a minimum design rating of IIC 55 between stacked residential spaces [1], which can be a challenging value to meet in non-carpeted, wood-framed construction without a concrete topping [2]. IIC ratings are determined by carefully controlled laboratory measurements. In the field, Apparent IIC (AIIC) measurements are used, per the measurement procedure defined in ASTM standard E1007 [3]. A floor-ceiling assembly which performs well in terms of airborne noise isolation (as determined by its Sound Transmission Class – STC – rating), may not necessarily perform well in terms of IIC.

In multi-unit wood-framed residential construction, floor-ceiling assemblies are typically constructed of insulated "I" floor joists. The construction between the floor joists and the finished floor will typically include one or more layers of wood sheeting, as well as an impact insulation layer made of a compressible material (e.g. high density glass fibre, foam, rubber). The finished flooring essentially "floats" above the impact insulation layer, which reduces the efficiency of vibration transmission to the structure. Below the floor joists, the ceiling construction typically consists of two layers of gypsum boards, either 13 mm or 16 mm thick. Airborne and impact noise isolation performance is improved by mounting the ceiling gypsum boards to resilient channels, which in turn are mounted to the floor joists in the perpendicular direction. When properly installed, resilient channels de-couple the ceiling gypsum boards from the floor joists. This results in significantly reduced transmission of vibrations, and therefore of structure-borne sounds due to impacts, compared to otherwise similar constructions with gypsum boards rigidly affixed to floor joists.

Ceiling constructions that include resilient channels must be carefully built to ensure that the resilient connection between gypsum boards and floor joists is maintained. One challenge in achieving this is that fasteners affixing gypsum boards to the channels are typically long enough to penetrate the bottom chords of floor joists, essentially defeating the resilient connection across the web of the resilient channel. Therefore, the ceiling installers must take steps to ensure that the location of floor joists are known, and avoid installing gypsum board fasteners for either layer of gypsum boards which are directly below the floor joists. Errant fasteners are a common construction deficiency for assemblies that include resilient channels, which significantly reduces AIIC performance.

## 3 Case studies

### 3.1 Project A

The project is a three-storey condominium building, totaling 37 residential units. Complaints were raised by occupants/owners at the time of the one year performance audit required by the Tarion Warranty Program in Ontario Canada. The floor-ceiling assembly construction is described below:

- Finished hardwood flooring, 19 mm thick
- 19 mm oriented strand board
- Foam impact insulation layer, 6mm thick
- 19 mm oriented strand board sub-floor
- Engineered wood "I" joists, spaced 406 mm O.C.
- 90 mm fiberglass insulation between floor joists
- 13 mm resilient channels
- 2 layers of 13 mm gypsum board, type "C"

Properly installed, this floor-ceiling construction was expected to test to AIIC 50 or more. Initial testing completed in a sample of four stacked residential unit pairs yielded scores below expectations, which suggested a construction deficiency.

Next, it was required to identify the remaining floor-ceiling assemblies between residential units that were

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performing below expectations for impact noise insulation. To expedite measurement collection, “mini” impact tests were completed between stacked unit pairs throughout the building. The “mini” tests consisted of using only two of the four tapping machine positions specified in ASTM E1007. Rather than performing background sound level and reverberation time measurements in each lower unit as required by ASTM E1007, these measurements were completed only for a small portion of the tests, and applied at other areas. Adjustments were made to the calculations based on a visual estimate of the amount of sound absorption in the lower unit, as compared to the spaces where reverberation times were measured. Low background sound levels were ensured by switching off any significant background noise sources (e.g. unit ventilation systems). The resulting AIIC scores were used on a pass/fail basis only, to identify floor-ceiling assemblies likely to have construction defects. The simplified testing allowed all unit pairs to be tested within far less time than would be required for full AIIC measurements.

Following “mini” impact testing, inspections of the lower unit ceilings were completed within several units, spanning the range of measured AIIC scores. The inspection procedure involved removing a portion of the ceiling drywall while leaving the resilient channels in place, in a central area of the room. Then, the number of intersecting resilient channels and floor joists which contained one or more drywall fastener that penetrated the floor joist (thus precluding the resilient connection between these materials) was counted, along with the total number of visible resilient channel / floor joist intersections. This allowed the rate of improperly installed fasteners at resilient channel / floor joist intersections throughout the ceiling to be estimated, and compared to the AIIC result, as shown in Figure 1.

## 3.2 Project B

The project includes three buildings of stacked residential units. Each building includes two lower units (ground floor and basement), and two upper units. Occupants and owners of lower units complained of unacceptable levels of intrusive noise from the footsteps of upper unit occupants. The floor-ceiling construction is described below:

- Finished hardwood flooring, 19 mm thick
- 2 layers of 9.5 mm oriented strand board
- Glass fibre impact insulation layer, 6 mm thick
- 30 mm oriented strand board sub-floor
- Engineered wood “I” joists, spaced 406 mm O.C.
- 305 mm glass fibre insulation between floor joists
- 13 mm resilient channels
- 2 layers of 16 mm gypsum board, type “X”

The expected minimum impact insulation performance for the floor-ceiling design was AIIC 52. AIIC tests were completed within bedrooms and the main living-dining areas for a total of six unit pairs throughout the three buildings – a total of 18 AIIC tests. All but two of the tested floor-ceiling assemblies failed to meet the minimum performance expectation, which strongly suggested a construction deficiency.

Inspections were completed within nine of the 18 tested assemblies. For each inspection, both layers of ceiling gypsum boards were removed in each of the lower unit rooms, for the complete ceiling area between bulkheads and demising walls. The resilient channels remained in place. The total number of visible resilient channel / floor joist intersections was counted, along with the number of these in which errant fasteners had been installed which bridged ceiling gypsum boards to floor joists. This allowed the percentage of resilient channel / floor joist intersections with errant fasteners to be compared with the AIIC score, as shown in Figure 1.

## 4 Results

Figure 1 below shows the relationship between the rate of bridged resilient channel / floor joist intersections and the AIIC score for both Project A and Project B. Figure 1 also includes best-fit lines and correlation coefficients (r) for each project. The data show that AIIC performance drops significantly as the occurrence of bridging fasteners increases. In Project A, a rate of 16% reduced AIIC performance by four points, and a rate of 48% reduced AIIC performance by nine points, relative to one test scoring AIIC 52 in which no errant fasteners were found. In Project B, AIIC performance was reduced by two points for a rate of 8%, and eight points for rates of 58% and 62%, relative to the minimum performance expectation of AIIC 52.

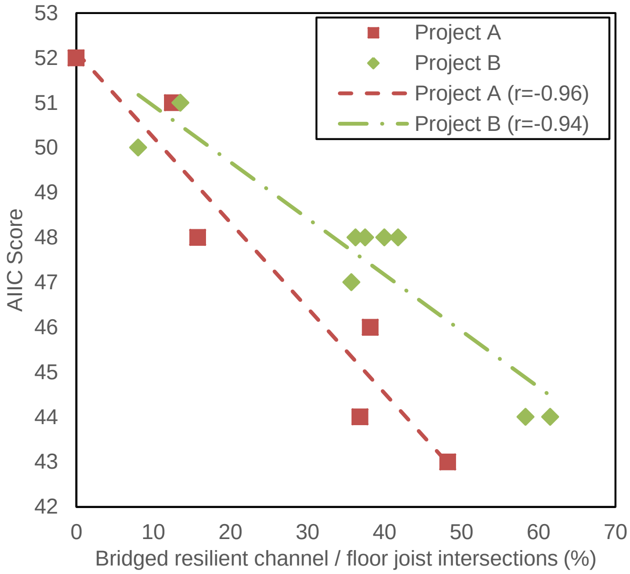

**Figure 1:** Relationship between AIIC scores and the percentage of bridged resilient channel / floor joist intersections

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# IMPROVING ASTC PERFORMANCE OF AS-BUILT WOOD-FRAME DOUBLE-SHEAR PANEL WALL ASSEMBLIES

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## 1 Introduction

As noted in the initial comparative study on this specific subject [1], acoustical engineers often encounter designs specifying multiple cavity partitions, with the expectation that they will provide equal or greater sound transmission loss performance than a single cavity partition of similar overall mass and dimension. That study confirms that this is not generally true, in particular for double-stud wood-frame and drywall demising partitions with structural shear panels on the inner faces of the studs. Using field results, it concludes that such configurations should be avoided in design where the goal is to achieve Sound Transmission Class (STC) ratings of 50 or higher. It also notes that these conditions nevertheless appear in the field with a high risk of not conforming to building code requirements [2]. Options to improve the performance of these walls were previously suggested [1], but had not been field verified. This article compares field performance of several partitions, and presents the acoustical effects of a commonly encountered shear configuration and mitigation scheme.

## 2 Background

### 2.1 Wood stud frame walls

In wood frame buildings, typically up to 6 storeys, the wood stud walls are often part of the load bearing structure, and as such, those walls require a shear panel. Commonly, this involves adding a plywood or OSB panel on one side of the studs, followed by the required layers of drywall to achieve the fire rating. For various reasons, but often for separate plate floors, a double-stud wall is used; one on each floor plate. Thus, for load bearing, shear panels for these walls are required on both stud sets. In modern building practice, the sheathed walls may be prefabricated or the framing is constructed flat on the floor with the sheathing layer on top, and then the wall is stood up in place. This results in stud cavities open on the suite side, as preferred by builders to add services and insulation prior to the drywall finish facings. This is repeated on the other side of the demising assembly. For a single floor plate, the second stud set does not include sheathing and creates a 3-leaf system (2 cavities). For separate floor plates and a shear panel on the inside of each stud set, a 4-leaf system results (3 cavities; 2 insulated cavities, and a small un-insulated cavity between).

As described in the previous study [1], the fully unsheathed assembly is given in the NBC supplementary tables [2] as W13 (a or b), rated at STC-57, with insulation between both sets of studs and one layer of type X drywall (13 mm or 16 mm) on each side. The two-cavity assembly is not listed, however, the endnotes in the supplementary table suggest a three point degradation in the STC rating with a single inner sheathing layer, which is consistent with past experience and discussed in reference [3]. The three-cavity assembly is also noted briefly in the end notes of the supplementary table [2] where it is noted that this “may drastically reduce the STC value”, but no specific value is assigned. These are shown schematically in Figure 1.

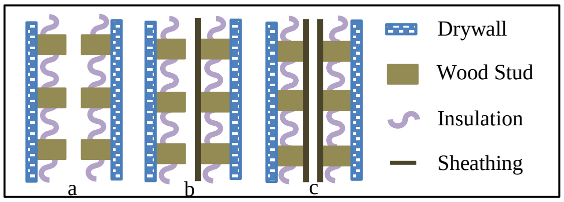

**Figure 1:** a) single cavity; b) double cavity; c) triple cavity.

HGC Engineering compared [1] non-shear (a) to double shear (c) field results with laboratory results for (a) and (b).

### 2.2 Coupling

There are two main sound transmission mechanisms between the multiple layers of the assembly: solid stud connection and airborne coupling via resonant cavity (mass, damping, and stiffness are the main factors relating to transmission within each material layer).

There is no solid connection in the non-shear double stud assembly (a), hence the high rating. In the two-cavity system, the inner layer of sheathing is solidly coupled via the stud to an outer drywall layer on the same stud. This connection is much stronger than the airborne coupling in that part of the assembly; however, this drywall-stud-sheathing assembly is still only airborne coupled to the other layer of drywall resulting in the 3-point degradation.

In the 3-cavity system, each stud assembly is dominated by solid coupling, and these two assemblies are separated by only a small (25 mm or less) un-insulated cavity with strong airborne coupling at a resonant frequency, within the STC frequency range. These assemblies are rated even lower, and with less consistency due to the close coupling.

### 2.3 Comparison of typical assemblies

As noted in the previous study [1], there is good agreement between the lab and field data sets. In both single and double cavities, the field performance is reduced at higher

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frequencies due to flanking, but gives similar STC ratings and curve shapes. The triple cavity is only measured in the field. As noted in the supplementary table notes [2], the double cavity rating (STC-54) is only 3 STC-points below the single cavity; however, the low-frequency degradation is responsible for the reduced STC rating, despite the boost at higher frequencies. The average triple-cavity assembly measured below the target with ASTC-49, with reduced performance throughout the frequency range but dominated by the low frequencies. The note in the NBC supplementary tables is accurate in discouraging these assemblies.

## 2.4 Possible mitigating assemblies

From the foregoing, these conditions should be avoided in design by locating at least one of the shear panels on the finish side of the studs. Other alternative may be considered in future, however, a recent building project included double shear panels, and the structural design could not feasibly be changed, thus, via mock-up tests, and final measurement upon substantial completion, the application of resilient channels was studied.

# 3 Measurement results

## 3.1 Mock-up

The subject site was under construction and site conditions were not ideal for mock-up; but it was intended that the trend and best estimate of performance from the addition of proposed mitigation could be established. Sound isolation of one partition, comprising double 89 mm studs separated by 25 mm with a layer of 11 mm sheathing on the inside face of each stud, 90 mm batt insulation, and 16 mm type X drywall on each finished side, fastened via resilient metal channels on both sides, was measured to be ASTC-52. A second partition was prepared with the same construction, except only one side used resilient channels. However, the room configuration gave rise to measurement contamination by excessive high-frequency airborne flanking, with a rating of only ASTC-44. Mathematically rejecting high frequency flanking suggested that this partition may achieve a rating of about ASTC-47 to 50. While this was not rigorous, even if it did achieve ASTC-50, it was only marginal at best.

A third partition with the same general construction but with 140 mm double studs and 125 mm insulation with one layer of 16 mm type X drywall on each face was also measured. Despite contamination and small rooms, the ASTC calculation gave an estimate of about ASTC-48. As this partition was to have an extra layer of drywall on each face, without resilient channels, it was further estimated to achieve a rating in excess of ASTC-50. Given the room sizes, this cannot be formally field confirmed.

## 3.2 Final measurements

The double-stud, double shear walls were then constructed using resilient channels on each face. Three field measurements resulted in an average rating of ASTC-53, ranging from ASTC-49 to 55, demonstrating marginal to robust compliance with the target.

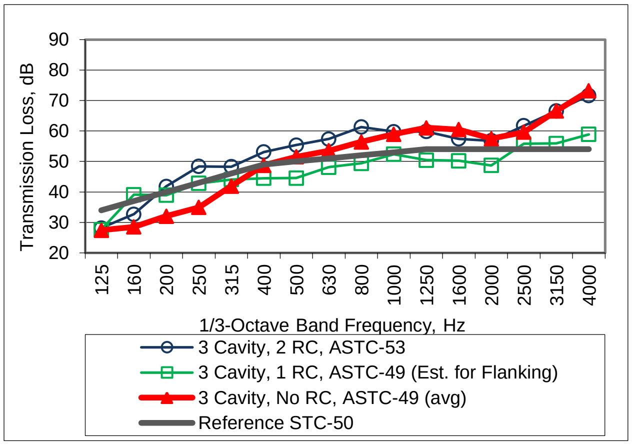

**Figure 2:** Mock-up apparent transmission loss results

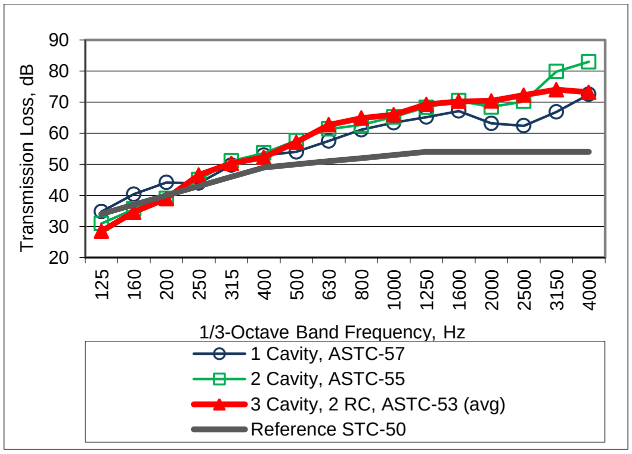

**Figure 3:** Final apparent transmission loss results

# 4 Conclusion

Field measurements have verified that the performance rating of partitions with double-stud and internal double-shear panel constructions do not reliably meet ASTC-50. Mitigation using resilient channels to fasten the finished drywall on each face have been shown to result in a four point increase resulting in generally compliant constructions. Adding a second layer of drywall to each side is tentatively expected to also achieve acceptable results, but only with deeper (140 mm) studs.

# References

[1] A. Lorimer and J. Tinianov, STC Ratings of Drywall Partitions With and Without Structural Sheathing, *Acoustics Week Proceedings*, 2015.

[2] National Research Council Canada. National Building Code of Canada, Volume 2. 2010.

[3] W. Gastmeier and M. Wu, Field Sound Transmission of Demising Walls and Floor / Ceiling Assemblies. *Internoise 92 Proceedings* Volume 2. 1992.

# CONTRIBUTION OF INTERNAL ASSEMBLIES TO WOOD-FRAME FLOOR/CEILING ASTC PERFORMANCE

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## 1 Introduction

In wood-frame buildings, internal walls directly mounted to the joists above (i.e., penetrating any drop ceiling) provide a flanking path for considerable potential vertical sound transmission, decreasing the Apparent Sound Transmission Class (ASTC) performance of the overall as-built assembly. With the National Building Code transition to regulating field ASTC performance from design partition STC performance, flanking paths such as these have the potential to change the acoustical performance of an otherwise well-built floor/ceiling assembly even with reasonable perimeter flanking controls at demising walls. This article presents a comparison of field measurements demonstrating the acoustical effects of flanking through internal walls mounted directly to the joists of the wood-frame floor/ceiling assembly above.

## 2 Background

### 2.1 2015 National building code of Canada

In 2015, a new National Building Code of Canada was issued, with a revised standard for evaluating the acoustical performance of a separating assembly for a dwelling unit. Prior to this change, the 2010 National Building Code had indicated that any “dwelling unit shall be separated from every other space in a building in which noise may be generated by construction providing a sound transmission class rating not less than 50.” [1] This requirement, which subsequently holds as the existing minimum STC requirement by the 2012 Ontario Building Code, applies to only the demising construction, which is tested in accordance with ASTM E-90 within a laboratory.

The 2015 National Building Code revised this requirement to specify either an STC rating of not less than 50 for the separating assembly (assessed as before) in conjunction with the adjoining assemblies, or an ASTC rating of not less than 47 for the “separating assembly and adjoining constructions” as a whole. [2] This second option offers a national standard for evaluating field measurements of a separating assembly, which intrinsically include flanking from adjacent walls and any other potential transmission paths. Since this publication, the Ministry of Municipal Affairs has issued a 2016 proposal to change the 2012 Ontario Building Code to match those of the revised national code requirements [3].

In coordination with the new ASTC requirements, the National Research Council Canada has created “SoundPaths,” an online tool for predicting the ASTC of a separating assembly when considering flanking from the adjoining components. While the web tool is yet to be fully developed, results from the existing version of the program have been compared to field results from applicable case studies, and discussed further herein.

### 2.2 Wood frame internal walls

In wood frame buildings, typically up to 6 storeys, internal wood or steel stud walls often terminate at a drop ceiling (as shown in Figure 1a). This leaves a continuous air gap between the dropped ceiling (usually on isolating resilient channels) and floor joists above, which includes insulation. With this configuration, internal walls are structurally disconnected from the floor joists above, effectively reducing the number of adjoining constructions from the separating floor/ceiling assembly.

**Figure 1:** A (Left): studs terminate at drop ceiling, B (right): studs terminate at joists.

An alternative configuration used by architects in wood frame buildings extends internal wood or steel stud walls through any drop ceilings and up to the floor joists above. As shown in Figure 1b, the double top plate is sandwiched between the wall studs and the floor joists, creating a rigid connection between the two building elements. This detail can provide a flanking path through the internal wall studs, through the top plate, and into the floor joists, where sound from below is transmitted into the space above the floor.

The resulting total sound transmission class of the in-situ floor/ceiling assembly is evaluated by logarithmically adding the individual STC rating of the floor/ceiling construction, with each STC rating attributed to sound transmission through an adjoining wall and up to the space above. Note that the existing version of the SoundPaths online tool assumes the latter configuration (i.e., Figure 1b) for all vertically stacked wood frame building sound transmission predictions.

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# 3 Measurement data

## 3.1 Laboratory data

Published laboratory measurement data for a wood frame floor/ceiling assembly was readily available from the 2012 Ontario Building Code MMAH Supplementary Standard Table SB-3 [4]. For comparative purposes, a type F14c floor/ceiling assembly from Table SB-3 was considered, consisting of one layer of 15.5 mm plywood sheathing with a 25 mm gypsum/concrete topping, supported by wood floor joists spaced at not more than 610 mm on-centre with acoustical fiberglass batt insulation in the joist cavity (no thickness indicated), 13 mm resilient channels spaced at 400 mm on-centre, and one layer of 15.9 mm type 'X' gypsum board on the ceiling side. This assembly is listed to have a design rating of STC-60, with the transmission loss shown in Figure 2.

## 3.2 Field measurements

Measurements to test the performance of this OBC type F14c assembly were required on a recently constructed stacked townhome building to assess compliance with the Ontario Building Code requirement of STC-50. One ASTC test was conducted in a relatively small source room below the floor/ceiling test specimen, with a higher ratio of wall area to the area of the separating assembly ($A_{SA}$). A second ASTC test of the same floor/ceiling assembly was conducted in a larger source room, resulting in a smaller ratio of wall area to the area of the separating assembly. Wall area to floor/ceiling area ratios for these source room configurations are summarized below, and measurement results from the subsequent ASTC tests are summarized in Figure 2.

# 4 Discussion

## 4.1 Comparison of adjoining constructions

As shown in Figure 2, both field assemblies tested lower than the laboratory performance of the floor/ceiling construction above. The difference between STC and ASTC can be attributed to various flanking paths, either common or unique to each test. One flanking path that is different for each field test can be attributed to the variance in wall area between the two source rooms (detailed in Table 1). As shown in Figure 2, the floor/ceiling assembly above the smaller room (i.e. higher $A_{WALL}$ to $A_{SA}$) performed four STC points lower than the floor/ceiling assembly above the larger room.

The ASTC spectral curve for each of the two tests follows a similar trend, indicating that the sound transmission paths between the two tests are similar in characteristic flanking and main separation assembly. For example, a largely unique flanking path to one test, such as a hole in the test specimen, would result in a different spectral result (i.e., different curve shape) measured above in comparison to another test without this path. Results with a similar performance spectrum and lower ASTC rating may characterize a common flanking path which is more dominant in one test than the other.

**Table 1:** Variance in wall area between source rooms

| | Room 1 | Room 2 |
|---|---|---|
| Internal $A_{WALL}$ to $A_{SA}$ Ratio | 140 % | 40 % |
| Demising $A_{WALL}$ to $A_{SA}$ Ratio | 73 % | 97 % |
| Total $A_{WALL}$ to $A_{SA}$ Ratio | 213 % | 137 % |
| Measured Floor/Ceiling STC | ASTC-49 | ASTC-53 |

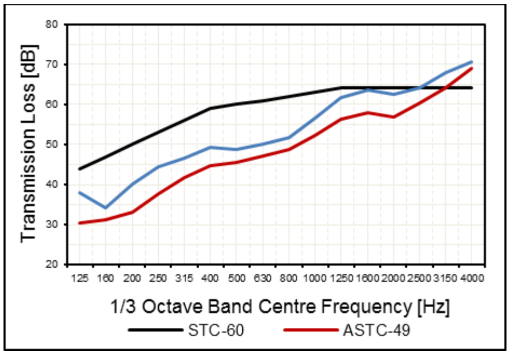

**Figure 2:** Transmission Loss Results

## 4.2 Possible mitigating assemblies

This potential flanking path may be mitigated by securing internal wall studs from below the ceiling drywall (Figure 1a), providing a structural disconnection from the floor joists above. Alternatively, wall studs which protrude through the ceiling and up to the joists can be separated from the joists using neoprene plate isolators, or the internal wall drywall can be secured to the wall studs using resilient channels; however, the latter of these alternatives is expected to be less practical. These measures have not been evaluated herein.

# 5 Conclusions

Preliminary results from a case study support the expected trend of lower floor/ceiling ASTC performance with higher wall area within buildings in which the internal walls are rigidly secured to the floor joists. Following steps could include sound intensity measurements to quantify sound power entering or leaving each room component, with focus on both internal walls and dwelling unit demising walls. Nevertheless, further investigation is required to develop a more detailed relationship between wall area and floor/ceiling ASTC performance.

# References

[1] National Research Council Canada. National Building Code of Canada, Volume 1. 2015.

[2] National Research Council Canada. National Building Code of Canada, Volume 2. 2010.

[3] Ministry of Municipal Affairs. Proposed Change to the 2012 Building Code O. Reg. 332/12 As Amended, 2016.

[4] Ministry of Municipal Affairs. Ontario Building Code MMAH Supplementary Standard SB-3, 2012.

# EFFECT OF INSUFFICIENT ADHESIVE ON ASTC PERFORMANCE IN CONCRETE PARTITIONS WITH LAMINATED DRYWALL

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## 1 Introduction

Based on experience of the authors, the sound isolating performance of properly cast concrete partitions is consistent and robust. However, it has been observed in the field that drywall layered on top of concrete partitions may, in some cases, have resulted in significantly degraded sound isolation performance of these partitions. This article presents a comparison of field measurements demonstrating the significant effects of insufficient adhesive to drywall-laminated concrete partitions, as well as “as-built” corrective methods to improve the sound isolating performance of drywall-laminated concrete partitions.

## 2 Background

In many concrete buildings, it is common to include a layer of laminated drywall on top of poured concrete partitions. While sound isolating performance of properly cast concrete can generally be consistently determined, the inclusion of laminated drywall may occasionally cause these partitions to underperform with respect to sound isolation.

A standard providing directions for application of gypsum board with adhesives to interior masonry or concrete walls (ASTM C-840 [1]) defines a measure of application of adhesives as follows:

*When applying gypsum board to monolithic concrete, brick or concrete block, the adhesive shall be applied directly to the back of the gypsum board or on the wall in continuous beads not more than 12 in. (300 mm) on centers or daubs spaced not more than 12 in. (300 mm) on centers each way.*

It has been frequently observed in the field that these directions are not frequently being followed, resulting in multiple variously sized cavities on both sides of drywall-laminated, poured concrete-partitions that are formed by the gaps between adhesive beads. This has resulted in concrete partitions, otherwise expected to exceed the requirements of the applicable building code, to underperform with respect to sound isolation. In some more extreme cases, this has resulted in concrete partitions failing to meet the requirements of the applicable building code.

## 3 Field measurements

Sound isolation measurements in the field (Sound Transmission Class, STC, as defined by ASTM E-336 [2]) show that drywall laminated concrete partitions occasionally drop in performance due to resonances localized to the surface of the drywall, within the 200-500 Hz frequency range. The resonant frequency, as well as the depth and width of the resonance, varies by case. This is considered to be relative to the effective size and depth of the cavities formed between the drywall surface and the porous concrete.

These gaps can often be observed in the field by tapping the drywall surface. Alternatively, any pockets of air between the laminated drywall and poured concrete wall can be detected by monitoring the sound field inside the receiving space during a sound isolation field measurement.

Measurement results, as tested by HGC Engineering on recent projects, are shown in Figure 1. These measurement results were obtained from condominium buildings as part of an assessment of their compliance with the building code requirement of STC-50. Published laboratory measurement data for a poured bare 200 mm thick concrete wall was obtained and included for comparison [3].

It should be noted that in field conditions, flanking paths and other deficiencies exist, including the presence of other voids in the concrete or its surface. However, the test results presented below are field test results that were each clearly noted to be affected by the effect of insufficient lamination of drywall.

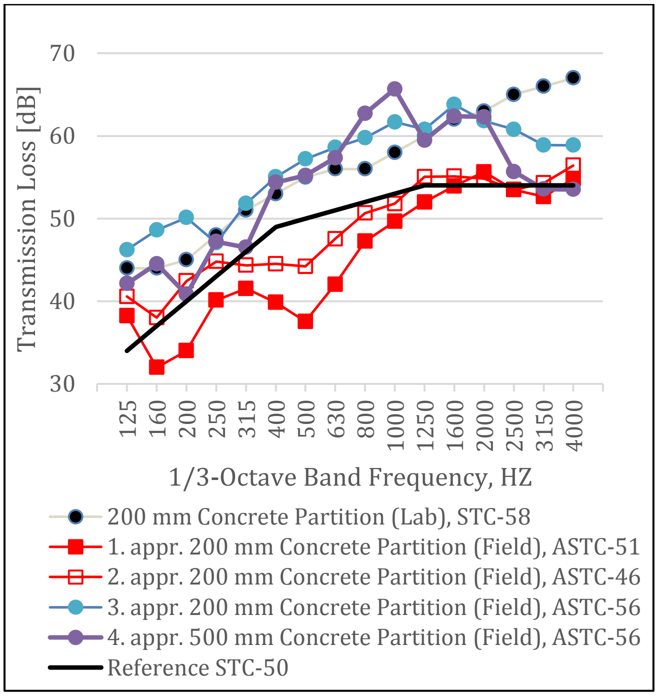

**Figure 1:** Transmission loss results

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# 4 Discussion

## 4.1 Observations

As can be seen from Figure 1, test number 1 is clearly limited by a resonance centering at the 500 Hz range, with a rating of ASTC-46, which did not meet the STC-50 requirement of the applicable building code. Test number 2 shows a similar, although less steep resonance with a result of ASTC-51, which just passes the requirement of the building code.

Test number 3 shows a result that is within the expected performance of the partition. It should be noted that even when applying adhesives as per the ASTM-C840, cavities are still formed, although the tighter grid translates to an absence of the resonance.

An extreme case is test number 4, a 500 mm thick poured concrete wall with both a theoretical performance of well STC-60, as well as an expected field performance of over STC-60, considering typical flanking paths within a concrete building. This assembly performed in the field with a rating of ASTC-56. The performance was mostly limited by observed insufficient drywall lamination on both sides of the assembly.

## 4.2 Mitigation considerations

As a mitigative effort, most direct solution would entail removing the drywall layer and reapplying the adhesive as per the ASTM-standard. At the time of this paper, no field test data for a wall following such procedure was available. However, the authors are expecting to perform such a test in the near future.

Removing and reinstalling a complete layer of drywall is not always the most cost-effective solution, and other solutions have been observed at construction sites to mitigate this poor lamination condition. In one instance, instead of removing the drywall layer in a finished and occupied condominium, a contractor has decided to fasten the insufficiently laminated drywall layer by using concrete nails at a 150-mm grid, resulting in approximately 700 nails being added to a small bedroom assembly. This solution reduced the drywall-to-concrete cavity size significantly, thus, effectively damping the resonance and ultimately increasing the sound isolation performance. While this measure only raised the STC performance it by six points, this resulted in a rating of ASTC-52, which passes the requirements of the building code.

# 5 Conclusions

The foregoing confirms that drywall layered on top of concrete partitions degrades the partitions' sound isolating performance when insufficient amounts of adhesive is applied. A degradation from the resulting cavities was demonstrated to reduce the ASTC-ratings in some extreme cases by 10 points in respect to the expected field-test value of concrete partitions. Mitigation without removal and reinstallation has not been shown to be highly effective, but may be sufficient in many cases.

# References

[1] ASTM C840-16, Standard Specification for Application and Finishing of Gypsum Board, ASTM International, West Conshohocken, PA, 2016, www.astm.org

[2] ASTM E336-11, Standard Test Method for Measurement of Airborne Sound Attenuation between Rooms in Buildings, ASTM International, West Conshohocken, PA, 2011, www.astm.org

[3] C.M Harris, Noise Control in Buildings, a guide for architects and engineers, 1994.

# BEAM-TRACING PREDICTION OF ROOM-TO-ROOM SOUND TRANSMISSION AND THE ACCURACY OF DIFFUSE-FIELD THEORY

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## 1 Introduction

The diffuse field prediction of acoustic transmission between two rooms is a significant aspect of building comfort. The sound field of a room is diffuse if the reverberant sound field is the same at every position in the room and reverberant sound waves are incident from all directions with equal intensity and random phase relations and [1].

Most of the existing standards for evaluating transmission loss of a partition wall are based on statistical theory [2]. However, this theory is unacceptable when the reverberant sound field departs from the diffuse field assumptions, like in long or flat rooms [2]. Although the existing diffusion model [2] and Odeon model [3] can accurately predict diffuse field theory in coupled rooms for diffuse and non-diffuse sound fields, they are not deterministic and accurate gemotrical acoustics approach like beam tracing.

In this paper, an extension of the existing beam tracing model for empty, parallelepiped rooms with specularly reflecting surfaces is proposed for predicting room-to-room sound transmission using energy approach (EBTM) which is the first work of room-to-room sound transmission using beam tracing technique. This new model is being used to investigate the accuracy of the classical diffuse-field formula (DFT) (L2=L1-TL+10log(S/A2)) [2] for both diffuse and non-diffuse configurations, which is the objective of this work.

## 2 Method

Similar to ref.[2, 3], the reference configuration has identical parallelepiped source and receiver room of 5m×5m×5m. All surfaces are specularly-reflected surfaces, local reaction and impedance boundary condition with 0.10 absorption coefficient; separated by a homogenous transmitting surface of 25 $m^2$ having frequency independent transmission loss (TL) of 20 dB. Source and receivers are kept 0.2 wavelengths away from surfaces and far apart so that the direct sound is ignorable; both receivers are placed near the middle of each room. The source is modelled as an omnidirectional sphere with a sound power level of 100 dB. At each frequency, f- input data for the source, receiver room, source and receivers, beam resolution and surface properties are entered in the model. Then, each beam is generated if it hits the transmitting surface in source room, part of the beam is reflected back and continue to propagate in the source room and checks if it strikes the receiver R1 and the complex-pressure contribution and SPL are calculated in source room; another part of the beam is transmitted into the receiver room and continues to propagate, checks if it encounters the receiver R2; the complex-pressure contribution and SPL are calculated in the receiver room. It is to be noted that no sound transmission from receiver to source room is considered in this model. To get the converged results for beam tracing models for reference configuration, 10580 beams and 50 reflections are required with computation time of 3 hours, 7 minutes and 38.93 seconds in a computer with an Intel i7 processor and 16 GB of memory.

## 3 Results

### 3.1 Energy-based methods

**Case 1: reference configuration (diffuse sound field)**

The accuracy of DFT is investigatied for reference configuration (diffuse sound field) by EBTM, ODEON results [3] and CATT-Acoustic (CAT-TM) simulation results as shown in Table 1 below.

**Table 1:** Comparison between DFT and the energy-based methods for the reference configuration (diffuse sound field).

| Room | DFT | EBTM | CAT-TM | ODEON |
|---|---|---|---|---|
| Source | 93.8 | 94.03 | 93.5 | 93.25 |
| Receiver | 76.02 | 74.24 | 76.2 | 75.11 |

In source room, the departure of DFT from all 3 methods and difference between each of them are within only 0.5 dB. Therefore, all three energy-based methods are quite accurate in predicting the diffuse field theory in source room.

In receiver room, the departure of DFT from EBTM is 1.78 dB; 0.18 from CAT-TM and 0.91 dB from ODEON. So, EBTM values are 1.5 dB and 0.8 dB lower than CAT-TM and ODEON respectively. Results shows that the energy-based methods shows higher discrepancies in predicting the diffuse field theory in receiver room while compared to the source room.

**Case 2: effect of room shape (for uniform absorption)**

In case 2, the shapes of both source and receiver rooms are varied while keeping the absorption of the surfaces uniform as case 1.

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**#1 Between a small cubic office room and large room.**

**Table 2:** Comparison between DFT and EBTM results for a small cubic office office room (source) and large room (receiver).

| Room | Dimensions | DF | EBTM | Departure |
|---|---|---|---|---|
| Source | 5m×5m×5m | 93.8 | 94.03 | 0.23 |
| Receiver | 10m×10m×10m | 73.8 | 71.59 | 2.1 |

The departure from DFT rises to 2.21 dB from 1.87 dB: 0.5 dB more deviation in receiver room in case 2 for only doubling the length of the receiver room i.e. long room (more non-diffuse sound field) from case 1: cubic room(more diffuse sound field). Results remained unchanged from case 1 for source room as expected since it is unchanged.

**#2 Between a large room and small cubic room.**

**Table 3:** Comparison between DFT and EBTM results for a large room (source) and a small cubic office room (receiver)

| Room | Dimensions | DFT | EBTM | Departure |
|---|---|---|---|---|
| Source | 10m×10m×10m | 91.58 | 91.15 | 0.43 |
| Receiver | 5m×5m×5m | 73.8 | 71.3 | 2.5 |

The departure of EBTM from DFT increases from 0.23 to 0.43 dB in source room; from 2.21 to 2.5 dB for receiver room for only doubling the length of source room for case #2 (more non-diffuse sound field) from case 1 (more diffuse sound field). So, increasing the length of the source room twice results in only 0.4 dB increase of departure in the receiver room from case #1.

**#3: Between two large rooms (10m×10m×10m)**

**Table 4:** Comparison between DFT and the EBTM results for two large rooms (10m×10m×10m)

| Room | Dimensions | DFT | EBTM | Departure |
|---|---|---|---|---|
| Source | 10m×10m×10m | 91.58 | 91.15 | 0.43 |
| Receiver | 10m×10m×10m | 68.93 | 71.3 | 2.65 |

The departure of EBTM from DFT are 0.43 and 2.5 dB for case #3 (more non-diffuse sound fields); 0.23 and and 0.78 dB rise in departure for only doubling the length of the reference (case 1) source and receiver room respectively. For increasing the length of the receiver room twice from case #2, the departure only increases by 0.15 dB.

**#4: Between two more larger rooms (25m×25m×25m)**

**Table 5:** Comparison between DFT and EBTM results for two large rooms (25m×25m×25m).

| Room | Dimensions | DFT | EBT | Departure |
|---|---|---|---|---|
| Source | 25m×25m×25m | 88.16 | 86.85 | 1.31 |
| Receive | 25m×25m×25m | 64.74 | 60.58 | 4.16 |

The departure of EBTM from DFT are 1.31 and 4.16 dB; 1.08 and and 2.29 dB increase for two large rooms of case #4 (more non-diffuse sound fields) for just increasing the length of both source and receiver room of case 1 by five times. Therefore, the departure of reverberant sound field from the diffuse field rises gradually with increasing the size of both source and receiver rooms from case 1 as expected. However, these depatur is considerably higher in receiver room compared to the source room of same size.

**Case 3: effect of surface absorption distribution**

The absorption distribution is made non-uniform from reference room configuration (case 1) by placing most absorptions in the ceiling while always keeping the same equivalent absorption area in both source and receiver room. Equivalent absorption area for reference configurations, 0.1×150 $m^2$ i.e. 15$m^2$ is distributed among the room surfaces keeping same equivalent absorption area as follows; 0.55×25 $m^2$ (ceiling)+ 0.01×125 $m^2$ (remaining 5 surfaces except ceiling) = 13.75+1.25=15 $m^{2.}$ The results for the effect of surface absorption distribution are shown for both source and receiver room in table 6.

**Table 6:** Comparison between DFT and EBTM for the reference configuration (non-uniform absorption)

| Room | Dimensions | DFT | EBTM | Departure |
|---|---|---|---|---|
| Source | 5m×5m×5m | 93.8 | 95.45 | 1.6 |
| Receiver | 5m×5m×5m | 76.02 | 79.42 | 3.4 |

For reference rooms (case 1) with non-uniform absorption distribution (more non-diffuse sound field), increases the departure from DFT to 1.6 dB and 3.4 dB, which are 1.42 dB and 1.53 dB higher in source and receiver room respectively compared to case 1 with uniform absorption (more diffuse sound field).

# 4 Conclusion

The results of this paper shows that in energy based methods, diffuse field theory is relatively more accurate for source room while compared to receiver room for reference configuration (i.e. more diffuse sound field); however its accuracy decreases significantly with changes in the shape of the room and distribution of its surface absorption (i.e. more non-diffuse sound field). The departure from diffuse field is particularly more significant with changes in absorption distributions while compared to the room shape while later further increase with changes of width and height of the rooms.

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# (A)STC TESTING WITH MLS: OLD DOG, NEW TRICKS

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## 1 Introduction/background

The original inspiration for this work comes from the Author's work in New Orleans as part of a team of engineers performing a leak detection survey on the 100 year old underground water infrastructure. The work was carried out using a device known as a "correlator" which detected water main leaks. The correlation of leak noise was made possible because the noise (or more accurately the vibration) a leak made on a pipe was completely random and unique, with no repeating pattern. The accuracy of the technology was quite impressive and still managed to work reasonably well on different types of pipe materials, through different fixtures, valves, and even around bends. The technology could even be used to help determine the health of the pipe being tested. Based on observations made of the capabilities of the leak correlator the Author wanted to know could it be applied to Building Acoustics in some way to get more information from standard acoustic field measurements?

The type of signal processing these leak "correlators" were using is similar to other devices that use a Maximum Length Sequence (MLS) pseudo-random noise signal to measure speakers or other room acoustics properties[1]. One common use of MLS systems is the computation of the reverberation time (RT60). The MLS is ideal for this because, like the leak noise on water pipes, it is unique and does not repeat, but it also happens to contain equal amounts of energy in all frequency bands. The method for measuring the RT60 using MLS is done by playing an MLS signal through a loudspeaker in a listening room (preferably in a corner), and then recording the reverberant sound field at another location. The measured result is then correlated against the excitation signal, which gives back the room's impulse response. From the impulse response one can use the Schroeder method [2] in order to calculate the RT60 in the space.

Another possible, but not very common, use for MLS is the (Apparent) Sound Transmission Class test, or (A)STC test, performed as per ASTM E336 [3]. Because of the author's experience with correlation in other fields and the fact that the requirement of the signal for the (A)STC test be a "random noise containing an approximately continuous distribution of frequencies over each test band" the author has begun performing (A)STC tests using MLS. The measurements are then used to correlate the results in the source and receiving rooms in order to explore if the signal can be correlated and what that correlated signal can tell us about the spaces being tested. An initial focus is on correlating the signal in the receiving room in order to obtain a suitable impulse response to determine the RT60 in that space.

## 2 Method

In general the testing is performed as per ASTM E336. Briefly the method involves playing a noise signal (MLS in this case) in one room, (the source room), that is adjacent to a second room (the receiver room), and measuring the reverberant sound field in both spaces. The difference in levels between the two spaces gives the amount of sound isolation the separating partition is providing. The results are corrected for the absorption in the spaces by measuring the background sound level and the RT60 in the receiver room.

Typically the RT60 would be determined through an impulsive balloon pop or other interrupted noise method. Since the MLS is to be used and recorded during the reverberant energy measurements it was determined that it is important to use a fixed point measurement method. Also in order to ensure the buildup of the reverberant energy the MLS should be set to repeat itself. In each case the measurement was performed for 30 seconds with a 5 second long MLS signal. This should result in multiple correlation peaks that are well separated from each other.

Once the data has been collected it can then be processed in MATLAB in order to correlate the data and obtain an impulse response. The impulse responses can then be further post processed in MATLAB or analyzed in another software package that follows the ISO 3382 [4] standard, in order to obtain the RT60.

## 3 Results

While multiple spaces had been tested with MLS the ASTM E336 test used a spatially averaged method in most cases, to measure the reverberant sound field in the source and receiver rooms. It was found that a fixed microphone method yielded the best results and the analysis has focused on tests performed between two offices of the same size (3.7 x 4.3 x 2.6 metres) at the Pinchin head office. The room was originally being tested as a result of complaints that sound isolation was poor between the two spaces. It was found that the partition had an (A)STC of 31 and was likely the result of the separating partition not extending up to the underside of the steel deck above.

### 3.1 Correlating an impulse response

In addition to recording the MLS in the receiver room it was of interest to record and compare to the MLS that would be

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recorded in the source room as well. The results of the measured signal correlated with the input MLS to the speaker are presented in Figure 1.

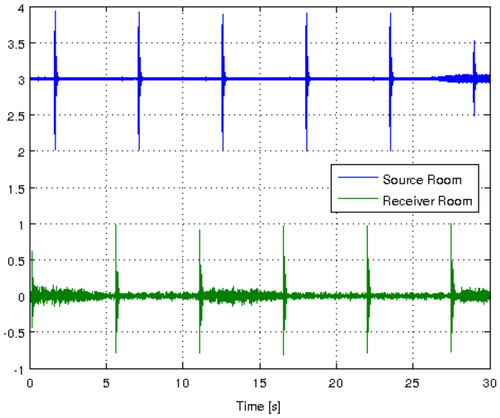

**Figure 1:** Correlation results for source and receiver rooms.

From Figure 1 we can see that the results from the correlation gave multiple impulse responses that are similarly spaced with, at first glance, a similar shape. It is clear upon closer inspection that the lower curve that represents the receiver room shows more random variation between peaks as compared to the upper curve that represents the source room. This result is not surprising since the signal has to travel through the partition into the receiver room.

## 3.2 RT60 determination

Based on the results shown in Figure 1 we have suitable data to be able to compute our RT60 via the Schroeder method. As an additional check traditional balloon pop impulse tests were conducted in the source and receiver rooms in order to verify the results from the MLS measurements. The results are averaged over multiple samples and summarized in Tables 1 and Table 2. In addition to the average result the Standard Deviation (STD) has been included to give an impression of how consistent the results are over multiple samples.

**Table 1:** RT60 results in source room.

| | 250Hz | 500Hz | 1kHz | 2kHz | 4kHz | 8kHz |
|---|---|---|---|---|---|---|
| Avg.MLS | 0.291s | 0.310s | 0.300s | 0.331s | 0.320s | 0.272s |
| Avg.IMP | 0.380s | 0.386s | 0.338s | 0.331s | 0.322s | 0.288s |
| STD.MLS | 0.001 | 0.001 | 0.001 | 0.003 | 0.003 | 0.003 |
| STD.IMP | 0.022 | 0.019 | 0.014 | 0.020 | 0.017 | 0.012 |

**Table 2:** RT60 results in receiver room.

| | 250Hz | 500Hz | 1kHz | 2kHz | 4kHz | 8kHz |
|---|---|---|---|---|---|---|
| Avg.MLS | 0.328s | 0.470s | 0.447s | 0.407s | 0.374s | 0.388s |
| Avg.IMP | 0.388s | 0.372s | 0.295s | 0.304s | 0.305s | 0.288s |
| STD.MLS | 0.047 | 0.052 | 0.046 | 0.029 | 0.006 | 0.012 |
| STD.IMP | 0.057 | 0.051 | 0.029 | 0.012 | 0.016 | 0.028 |

As can be seen from comparing the results in Tables 1 and 2 that the MLS RT60s are close to the impulsive balloon pop measurements in the source room but are consistently higher in the receiver room. We can also see that based on STDs of both methods in either room, the results are consistent over multiple samples, with the MLS tests in the source room being an order of magnitude more consistent compared to the impulsive balloon pops.

## 4 Discussion

Based on the results we can see that in the source room that the traditional impulsive balloon pops give results that are close to the results from the RT60 calculated from the MLS measurements, which is to be expected. While it was clear that an impulse response could be determined from the recordings of the MLS in the receiver room the RT60 results from those measurements are consistently high in the mid to high frequency bands. This result can be potentially explained by the fact that the partition separating the two spaces did not extend from slab to slab. It is theorized that the presence of a strong flanking path will couple the spaces together such that the system response of both spaces will behave in a similar way to two capacitors that are coupled together by a resistor would, thus extending the RT60. If this is the case then by following this method and comparing the difference between the RT60 determined by correlating a signal through the structure to an RT60 determined in the space itself may result in a quantitative test for the presence and the magnitude of flanking paths between two spaces.

## 5 Conclusion

Based on the results we can conclude that it is possible to transmit an MLS signal through a partition (or structure in general) and then correlate the signal to obtain an impulse response. Based on the limited amount of data the results would suggest that meaningful information can be determined from performing (A)STC testing in this manner. It is expected that if the two spaces had not been coupled together by a flanking path through the ceiling plenum then the RT60 results in the receiver room would have been much closer to the RT60 calculated by the more traditional method. However, even though the RT60's were different the STD showed a consistent result and the difference between the RT60 results could indicate the presence and magnitude of the flanking path between the two spaces.

The amount of data that was available for this work was limited since only recently it was discovered that fixed mic measurements were needed in order to obtain reasonably good results. Thus more testing is required before anything can be said conclusively.

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# HVAC DISPLACEMENT SYSTEM NOISE CONTROL – A NEW METHOD TO QUANTIFY NOISE CONTROL PERFORMANCE

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## 1 Introduction

The only plenum noise control calculation procedures that the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) currently considers are the ones that suit the big box on the exit end of an Air Handling Unit (AHU). In performing arts centres and in modern offices one is confronted with a different problem. Not a chamber at the end of a duct or an AHU but a whole room directly below the noise sensitive space, be it an office or an opera house. When Toronto's new opera house was being designed, there was no method available to measure a plenum's Insertion Loss, let alone a method to predict the anticipated noise levels. This paper will propose methods to do both.

## 2 Method

### 2.1 Concept

Top down Heating Ventilation and Air Conditioning (HVAC) systems dump the conditioned air from on high and return it down low. A displacement system reverses this route. A room (the plenum) is located below the audience chamber. It is pressurised with conditioned air, usually with the aid of distribution ducts to get an even distribution of air. Holes in the audience chamber floor allow the air to drift upwards displacing the air that is already there – hence the name. The air flows very slowly, typically at 0.5 m/s (100 fpm) thus virtually eliminating turbulence induced noise. Air is returned through large ducts in the upper reaches of the auditorium. An image of a typical displacement system is shown in Figure 1.

### 2.2 Analysis

When beginning the analysis of a displacement system's sound field a difficult question is immediately posed. Should one be concerned with the few openings that a listener might have a clear line of sight to? For example, the 4 or 5 openings one might see sitting on the orchestra level. Or should one consider the hundreds of openings that might be seen from a balcony or catwalk? Numerically, it is a difference of at least 25 dB. Ideally one should consider both scenarios but which one is more important?

To do that, the proposed procedure borrows from the early 20th century when sound in a room was first divided into two independent components: Direct and Reverberant. The displacement noise problem does not fit quite so neatly into these categories of Direct and Reverberant sound. But, it was determined that it doesn't have to. A concept of Near and Far Fields was developed both for calculations and measurements. The question still remained though, which field is more important the Near or the Far Field? It's also worth noting that the holes in the floor that the air flows through could be considered as a partially closed pipe. As such, will they display resonances? Only measurements could assist with that question.

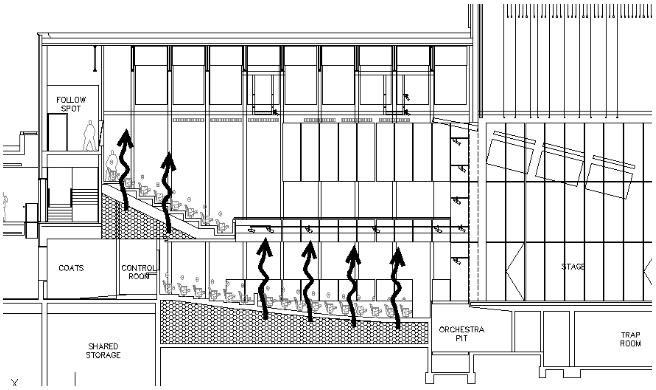

**Figure 1:** Longitudinal section showing the displacement system at The Esplanade, Medicine Hat, Alberta. Air is supplied through holes in the floor and returns through ductwork located in the ceiling space.

But before one moves on to the measurements, a subtle but important refinement of the procedure is required. Up until now the openings in the floor have been considered as individual sound sources, a bit like an array of loudspeakers. Sound starts in one room (the plenum) and propagates into the next as a series of new, smaller sound sources. It's a bit like Huygen's principle. And it's quite difficult to handle either conceptually or through measurements. The solution was to shift the method of confronting the problem; not as a collection of 100s of sound sources but rather as one room (the plenum) separated from the other (the audience chamber) by a barrier. In this case the barrier is a composite of the concrete floor and the openings in it, something very easily calculated with area ratios. Performance is quantified, as one would do with a normal Noise Reduction measurement. One has moved from a complicated 17th century scientific paradigm to an easily understandable mid-20th century noise control engineering solution.

## 3 Measurements

Measurements were performed in three venues, the Mississauga Living Arts Centre in Mississauga, Ontario (MLAC), The Esplanade Arts and Heritage Centre in

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Medicine Hat, Alberta and the Four Seasons Centre for the Performing Arts (FSCPA) in Toronto. Please see the summary in Table 1.

**Table 1:** List of venues

| Building | City | Volume ($m^3$) | Type of Diffuser | Plenum lining |
|---|---|---|---|---|
| The Esplanade | Medicine Hat | 5,450 | Mushroom | None |
| MLAC | Missis-sauga | approx. 13,000 | Seat pedestal | 100 mm |
| FSCPA | Toronto | 14,000 | Seat pedestal | 50 mm |

The near field was measured with the loudspeaker resting on top of a duct, close to the hole under examination. Measurements were then performed on either side of the hole, i.e. in the plenum then above in the audience chamber, first at floor level and then at ear level 1 m above the floor. Far field measurements were performed as one would an ASTM E-336 Noise Reduction measurement.

# 4 Results

## 4.1 Near field

Results for the Near Field measurements are shown in Figure 2. Note what appears to be resonance effects in the 250 Hz to 500 Hz range. Near Field measurements at ear level (1 m above the floor) show similar results although the suspected resonance effects are not as pronounced. At higher frequencies the attenuation is more pronounced as one might expect for the barrier effect created by the chair.

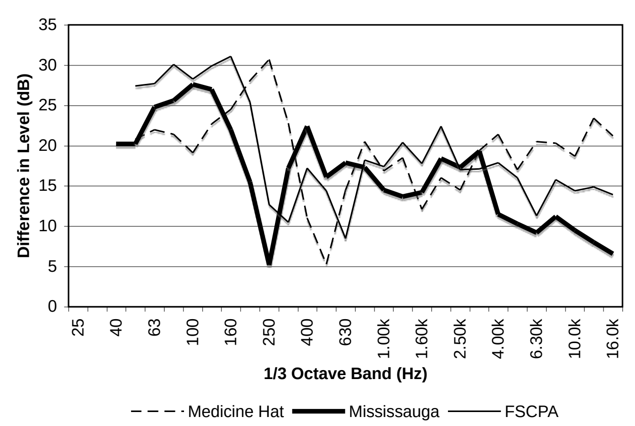

**Figure 2:** Measured near field noise reduction from the underside of a slab hole to the diffuser at the floor level immediately above.

## 4.2 Far field

Results from the Far Field measurements are shown in Figure 3. It might be noted that the presence of glass fibre lining had little effect on the Noise Reduction levels. MLAC had the thickest lining (100 mm), FSPAC 50 mm and The Esplanade none. MLAC has slightly higher attenuation but there's little consistent difference between FSCPA and The Esplanade.

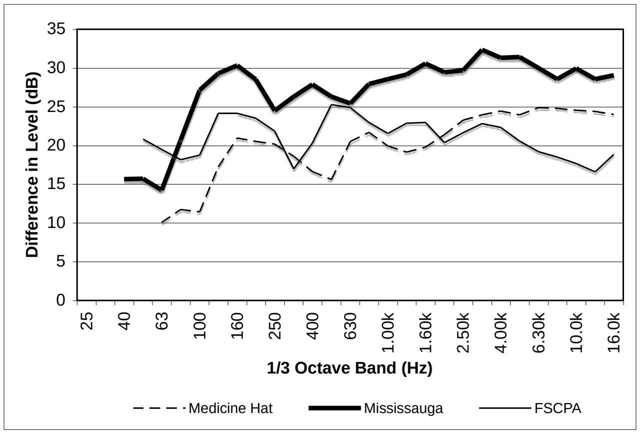

**Figure 3:** Measured far field noise reduction between the plenum and the orchestra level

## 4.3 Comparison

So the important question at the beginning was which field is more significant. It turns out it's the Far Field. At most frequencies, the Noise Reduction for the Far Field is lower than the Near Field. This means that the Far Field will be louder inside the auditorium.

# 5 Validation

Predicted and measured values using the Near and Far Field concept are shown in Figure 4. There is good agreement between the predictions and the measurements, except perhaps at low frequencies.

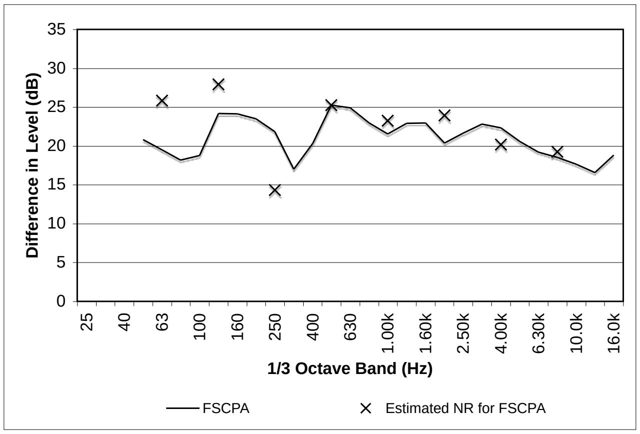

**Figure 4:** Calculated (X) and measured (–) near field noise reduction at the four seasons centre for the performing arts.

# THE APPLICATION OF NURBS TO ACOUSTICAL SCIENCE

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## 1 Introduction

Non-Uniform Rational B-Splines or NURBS are a mathematical construct developed by the Italian automotive industry in the 1960s. A NURB is to a 3D shape what a B-Spline is to a 2D curve. Once the purview of multi-nationals with large mainframe computers, for the past 15 or so years they can be found on personal computers in software platforms such as Rhino, among others. The impact of NURBS on architecture can be seen in the increasingly challenging geometries such the Guangzhou Opera House [1] and the wonderful new Philharmonie de Paris [2]. The rectilinear geometry paradigm that has dominated architecture since the beginning of the last century is beginning to wane. Acousticians were complicit in the rectilinear discipline because over that time if one wanted to do a reflection calculation, either by hand or computer, one had to cast reflections off a flat surface. The result was that the wonderful curves and domes used by architects in ages past have no longer been seen in recent buildings. NURBS can restore that exciting expression of geometry and, indeed, already have.

## 2 History

It is the author's observation that if one looks at the history of science or technologies such as our own, the important ideas of the day tend to focus on what could be measured or predicted at the time. For a good part of the 20th century, the concept of Reverberation Time ruled. That was because until the 70s or 80s, before the dawn of accessible computer power, that's all that one could measure or confidently predict.

Before NURBs were introduced to acoustics, geometries that focus sound were generally thought to be acoustically troublesome. This despite evidence to the contrary, such as barrel vaulted naves in churches and cathedrals. There are successful concert venues with barrel-vaulted ceilings, notably London's Wigmore Hall [3] and sections of rooms that benefit from domed ceilings, e.g. the balcony of Vancouver's Orpheum.

One of the most celebrated domes is in St. Paul's Cathedral, London. Please see Figure 1. There are two foci as the sound collected in the dome propagates towards the congregation below. By the time it gets there it is arriving at the listeners as lateral energy, which as we know, is an important ingredient for good acoustics.

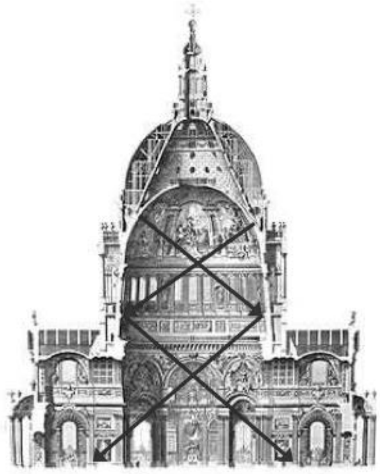

**Figure 1:** Focusing created by the dome in St. Paul's leads to beneficial lateral reflections directed towards the congregation

### 2.1 Experiment

Using the flexibility of NURB based design; a simple computer based experiment was performed. There are three important forms of focusing geometries: circular, hyperbolic and elliptical. The latter is the most interesting for acoustic reflector design. There are two foci in an ellipse and one can use that to advantage, as shown in Figure 2.

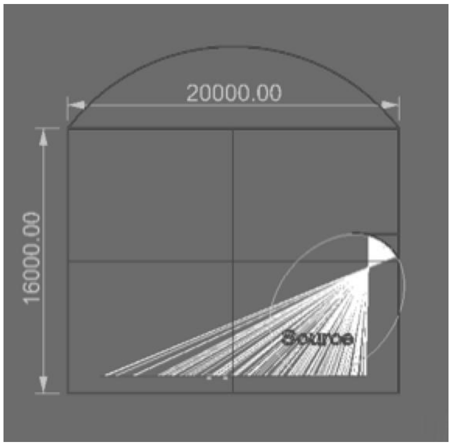

**Figure 2:** A focusing soffit reflector. The source on stage is at one of the reflector's foci and the focus of the reflected sound is at the other, high above the listeners' heads.

In this experiment the source on stage is at one of the ellipse's foci and the focus of the reflected sound is at the other. Three things to note: (i) The curved soffit reflector provides beneficial lateral reflections to the listeners. But, unlike side wall reflections, the soffit reflections come from above and thus are not subject to low frequency grazing

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incidence attenuation; (ii) the focus of the reflected sound is high above the listeners' heads; (iii) beyond the reflected sound focus the soffit reflector turns into a scatterer of sound, which has been optimised for uniform distribution of sound on the seating plain and to avoid "splash" to the wall beside.

## 3 Case studies

### 3.1 Queen Elizabeth Theatre, Vancouver

The author and his colleagues learned about the importance of instantaneous visual feedback from computer software during the renovation design of Vancouver's Queen Elizabeth Theatre [4]. This was, acoustically, a very difficult renovation because the owner's representative insisted on a seat count of 2800. This meant leaving the remnants of an acoustically lamentable, very wide post-war room and then trying to solve the problem. It was solved with green building software known as Ekotek, a package intended for light not sound, This allowed the design team, for example, to design balcony front reflectors hanging – in a mathematical sense in 3-D nowhere land – to be optimised to within less than a degree. But all this design power could only be rendered in flat surfaces. That was when the author and his colleagues started developing similar visual optimisations on curved surfaces, i.e. using NURBS.

### 3.2 Von Kuster Hall, London Ontario

Following the work on the Queen Elizabeth Theatre, the design of which was limited to rectilinear solutions, the hope of the author was to graduate the iterative acoustic design optimisations from flat surfaces to curved surfaces, thus, hopefully, expanding the architects' design palette. The budget for von Kuster Hall could not accommodate side wall balconies. Knowing how important soffit reflections are, as explained in Section 0, an unoccupied shelf was put in, as shown in Figure 3. Iterative visual optimisation of the soffit's geometry was done with a plug-in created by the author and his colleagues called the NURB Room Acoustics Tool, or NRAT [5]. NRAT is essentially a ray tracer that can reflect sound off curved surfaces.

### 3.3 Confederation centre, Charlottetown PEI

NRAT was also employed in the renovation design of the Confederation Centre in Charlottetown. A number of NURB based designs were proposed, including one using the principles explained in Section 0. In the end, the architects decided to use their own design.

## 4 Automated design optimisation

The design iterations for von Kuster Hall and the Confederation Centre were done "by hand". That is, after each iteration, the NRAT operator would change the geometry of the reflector in Rhino then run NRAT to find out the results. This took time, at most only 12 optimisation designs could be generated and tested in a day. It was decided to employ computer optimisation routines borrowed from the aerospace industry [6]. The optimisation tool is called SOAR. Where perhaps a dozen optimisation iterations could be done in a day, SOAR can do thousands.

**Figure 3:** von Kuster Hall, University of Western Ontario. What looks like a side wall balcony is an unoccupied "shelf" used to generate beneficial lateral soffit reflections.

## Acknowledgements

The author should like to recognise the contributions of Daniel Ruvalcaba and Kiyoshi Kuroiwa on the Queen Elizabeth Theatre project and, I'm sure, many others. Most of the coding for the NURB project was done by David Grant and Payam Ashtiani, for which the author is grateful.

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# A NOVEL APPROACH TO COUNTING WAVES IN A ROOM

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## 1 Introduction

Humankind is used to describing the world in three discrete spatial dimensions, with a forth one for time. Nature however does not observe discrete dimensions. Whether it be a leaf, a tree or a coastline, nature works between the integer dimensions, typically between the dimensions of two and three or sometimes between one and two. These are called fractal dimensions. And they are the hallmark of what is called chaotic behaviour. One of the methods that has been developed to determine the fractal dimension of a signal is to plot it against a time delayed version of itself [1]. This begs the question: is the acoustic field in a room chaotic. The author has tried, unsuccessfully so far, to determine if sound in a room is chaotic. D'Antonio [2] is of the opinion that it is not. It would seem, however, to make sense that it is chaotic; most natural system are, although to author's knowledge no one has yet proved that with measurements. Whether it is or isn't is not the topic of this paper. But one can use the methods of detecting chaotic behaviour to other aspects of an acoustic field; namely counting waves. Indeed, it was while trying to identify chaotic behaviour in impulse response functions that the method was developed.

## 2 Method

### 2.1 Measurements

Measurements were performed in 25 venues over the space of 25 years. Only 12 will be reported here ranging in type from concert halls, recital halls, proscenium arch theatres and rehearsal halls. All 12 were stage acoustics measurements, as opposed to audience chamber measurements. Further details on the measurement procedure may be found in [3] and [4]. The list of venues is shown in Table 1.

### 2.2 Analysis

Following the methods of chaos theory analysis, one needs to plot a given measurement, in this case p(t), against a time delayed version of itself. If one takes a typical impulse response function, and wants to look at a time delayed version of it, the simplest way is to take the time derivative, in this case dp/dt.

The result is a series of circles, each one representing a wave. Using a simple Matlab routine, the circles – and hence the waves – can be counted.

**Table 1:** List of venues

| Venue | City1 | Vol. (m3) |
|---|---|---|
| Centre in the Square | Kitchener | 16,632 |
| Glenn Gould Studio | Toronto | 4,587 |
| Hamilton Place | Hamilton | 29,907 |
| NAC Opera House | Ottawa | 37,452 |
| NAC Rehearsal Hall | Ottawa | 1,398 |
| Sony Centre Rehearsal Hall | Toronto | 1,918 |
| The Orpheum | Vancouver | 19,200 |
| Playhouse Theatre | Vancouver | 6,533 |
| Queen Elizabeth Theatre | Vancouver | 32,452 |
| Royal Theatre | Victoria | 15,240 |
| Theatre Aquarius | Hamilton | 12,526 |
| Theatre Aquarius Reh. Hall | Hamilton | 1,822 |

At this point the difference between reflections and waves should be clarified. The number of reflections is a theoretical construct. One of the things discovered in this study is that the number of reflections in a room cannot be measured. This is due to constructive and destructive interference of one reflection with another. The author choses the word 'wave' because that is what results when two or more reflections interfere with each other.

In 1950, Bolt et al. [4] developed a formula to predict the number of reflections in a room:

$$N = \frac{4pc^3t^3}{3V} \tag{1}$$

Measurements reported below show a vast difference between predictions from Equation (1) and what can be measured.

In 1995, the author suggested Revised Theory [6] might not be the most accurate predictor of sound levels on a stage. Revised Theory assumes an unoccluded direct sound and a diffuse reverberant field. Both assumptions are often violated on a stage. And with a wave counter, one can approximate the temporal division between the discrete and reverberant fields. Two sets of comparisons were made between Revised Theory preditions and linear regressions of the measurements. In the first set, unadulterated versions of the impulse response functions were compared with calculations based on an unadulterated versions of the Revised Theory calculations. In the second set, the direct sound was omitted from both the measurements and the calculations. This was done by nulling the first 5 ms on both the signal and in the calculation. Results are shown below.

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## 3 Results and conclusions

A typical plot of p(t) vs. dp/dt is shown in Figure 1. Note that the time axis is vertical, t = 0 is at the bottom of the graph. It's often said that a 2-dimensional plot of an impulse response looks like a Christmas turned on its side. Well if one plots p(t) against its time derivative dp/dt one gets a 3-dimensional plot and it really does look like a Christmas tree!

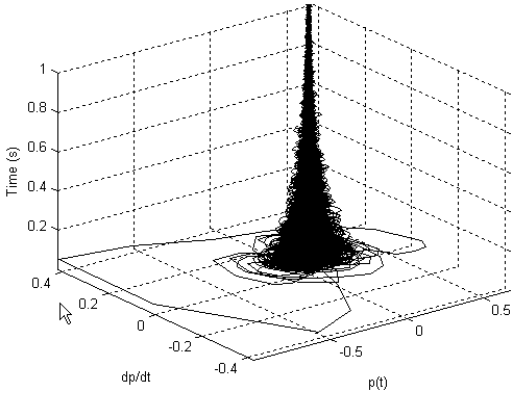

**Figure 1:** A 3 dimensional view of an impulse response function. The signal p(t) is plotted against time and its time derivative dp/dt. Note that the vertical axis is time. Each circle of this "Christmas Tree" impulse response represents a reflection.

As previously mentioned, there is a wide discrepancy between the number of reflections predicted and the number of waves that can actually be measured. A comparison is shown in Figure 2. There are three things to notice here. On the right side of the graph, the wave count is much, much lower than the predicted reflection count. This is almost certainly due to interference effects. Note also how the wave count curve (solid line) flattens out slightly as it enters the diffuse field. On the left side of the graph, the wave count is higher than the predicted reflection count. There are two possible explanations for this. All the measurements shown here were done in the close confines of a stage, which might explain a higher reflection density close to the source. And it could be the source itself, a 12 sided dodecahedron with 75 mm speakers. Hardly a point source when measured within a 7 – 8 m range.

As mentioned, two sets of comparisons were made between measurements and calculations. (The results quoted here are from Hamilton Place but the other venues showed similar results). A typical example of the unadulterated version is shown in Figure 3. The rms error between measurements and predictions is 1.91 dB for Revised Theory and 2.96 dB for linear regression. This contradicts the original hypothesis of the study. For the second set of comparisons, the ones with the first 5 ms deleted, the rms error between Revised Theory increases greatly to 6.11 dB. The rms error between the measurements and the linear regression decreases to 1.21 dB. Thus to answer the question if Revised Theory is an appropriate predictor of sound levels on a stage, the answer is yes. However if the direct sound is blocked, as it often is on a stage, linear regressions correlate better with measured sound levels.

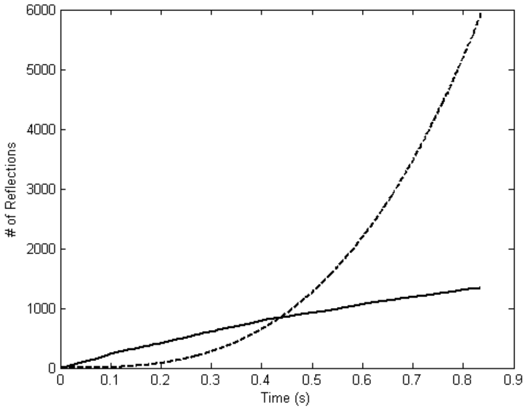

**Figure 2:** Comparison between measured reflection counts (solid line) and predictions from equation 1 (dashed line). The measured data came from the centre in the square, source at the soloist position, receiver at bass.

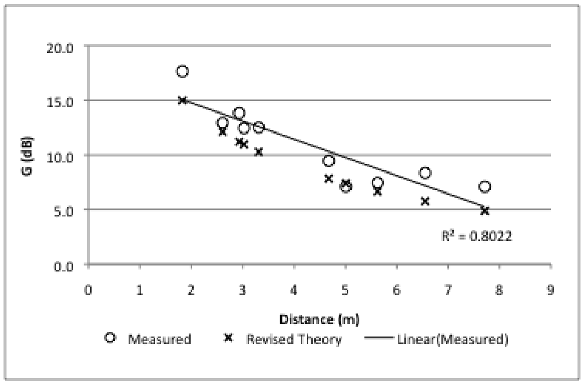

**Figure 3:** Typical comparison between measured data (circles) Revised Theory (x) and linear regression (line). The measurements were performed at Hamilton Place.

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# ACOUSTIC PERFORMANCE OF STUDY ROOMS - A CASE STUDY

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## 1 Introduction

A new building at an academic institution was built for the purpose of providing students with needed space for individual and group study. The building had quickly turned into a preferred space and is often heavily occupied. The study rooms are equipped with televisions and the walls are coated with a whiteboard layer, so that group discussion can be undertaken in addition to silent study. There have been numerous complaints from users of the study rooms about disturbances from the TVs and those speaking in adjacent rooms. Students noticed that conversations were easily audible, even when speaking at normal levels.

Two pairs of unoccupied study rooms were used to conduct tests and evaluate their acoustical performance. The Apparent Sound Transmission Class (ASTC) and Articulation Index (AI) ratings were calculated to determine if the study rooms are acceptable for students requiring a quiet workspace, while having their conversations kept private. The results of the study are presented in this paper.

## 2 Method

### 2.1 Inspection

Upon examination of the rooms, it was clear that the major flanking sound paths were gaps along the edges in the dividing walls, cut-outs behind the wall mounts for the TV's cables, and possibly, exposed return air grilles. The return air grilles led to an open plenum space, which was shared with other study areas and in close proximity to adjacent study rooms' exposed grilles. A plan view of all four rooms is shown in Figure 1. Room "A and B" were on a different floor than "C and B".

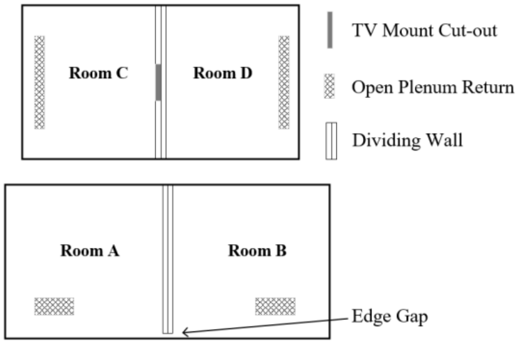

**Figure 1:** Plan view of tested rooms

The cut-out behind wall mounts were also placed on a dividing wall depending on the room, shown in Figure 2.

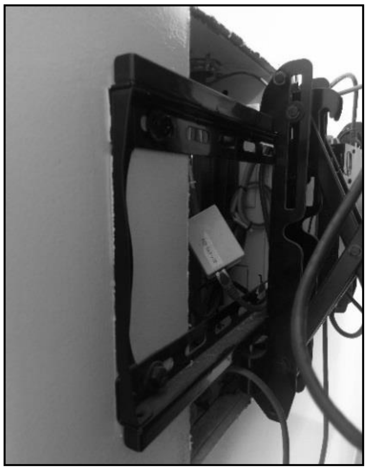

**Figure 2:** Wall extraction behind TV mount

### 2.2 Testing methodology

Four rooms in total were evaluated for the purpose of this study. The first pair, Room A and B, shared a dividing wall with an edge gap. The next pair, Room C and D, was on a different floor and shared a dividing wall with the TV mount shown in Figure 2, without an edge gap. This allowed for an individual analysis on both types of major flanking paths between the rooms. Testing to assess the open plenum return was done between Room A and B alone.

A pink noise generator was connected to a Brüel & Kjær omnidirectional speaker to produce sound in the room, and a Larson Davis integrating sound level meter was used to record 2-3 measurements in each room.

To calculate the reverberation time in each room, a full spectrum, logarithmic sine sweep was used to generate an impulse response within Odeon.

## 3 Results

### 3.1 Room conditions

Background noise levels were measured in each room and NC ratings were initially calculated to evaluate their conditions. These are presented in Table 1, along with the average reverberation times ($T_{30}$) across frequencies of 500 – 2000Hz, the most important range for speech [1]. Although Chapter 48, "Noise and Vibration Control" of the ASHRAE Handbook does not have any criteria specifically pertaining to study rooms, their indoor sound criteria for classrooms can be related as similar activities are undertaken in study rooms. Their design guidelines recommend a maximum of NC-30 for classrooms [2], and

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the study rooms had a suitable, low NC rating of 22-24. The $T_{30}$ times ranged from 0.4s – 0.7s; a reverberation time of 0.5s – 0.7s is desirable for speech and is not expected to cause any issues [3]. Though Room B has the sole $T_{30}$ out of this range, it was deemed acceptable for this study as it was marginally below 0.5s, and still under 1s. Speech intelligibility within a single room was therefore not a concern.

**Table 1:** NC and reverberation time of room A to D

| Room | NC | $T_{30}$ (s) |
|---|---|---|
| **A** | 24 | 0.6 |
| **B** | 23 | 0.4 |
| **C** | 22 | 0.7 |
| **D** | 23 | 0.6 |

### 3.2 Articulation index

Although the primary purpose of the study rooms is not to host confidential conversations, the AI can be a useful metric when assessing scenarios where speech intrusion is unwanted. The AI for each pair of rooms was calculated, including the speaker and receiver room being exchanged at the end of each test. The values were computed by subtracting the averages of the noise and background levels from the signal levels, equalling the signal to noise ratio. One-third octave band weighting factors were then multiplied to the signal to noise ratios. Summing the weighted signal to noise ratios totalled the articulation index, presented in Table 2.

The ASTC was calculated in a simplified manner, incorporating Equation (1) below.

$$TL = NR + 10\log_{10}(A/S\overline{\alpha}) \qquad (1)$$

The transmission loss across 125 – 4000 Hz was plotted against standard STC contours. Since flanking paths were known to be accounted for, this is effectively the ASTC. Values are shown in Table 2.

**Table 2:** Computed AI and ASTC results

| Path | AI | ASTC |
|---|---|---|
| **Room A to B** | 0.32 | 30 |
| **Room A to B*** | 0.32 | 30 |
| **Room B to A** | 0.17 | 30 |
| **Room C to D** | 0.35 | 27 |
| **Room D to C** | 0.46 | 35 |

*Open plenum return grille covered

## 4 Discussion

All of the results show that there is no privacy between the rooms [3], except for when Room A was the receiver and Room B was the source, there was marginal privacy. This is likely due to the fact that Room A had higher background levels, which resulted in negative signal to noise ratios (taken as zero when calculating partial AI). The test for Room A to B was repeated with the open plenum return grille covered, which showed no change in AI or ASTC. This suggests that it did not act as a major flanking path between rooms. However, the TL at 8000 Hz reduced by 5 dB with the grille covered. This could be as a result of the noise not entering the plenum area through the return as easily, and now having an additional reflection point within the room. The improvement in both AI and ASTC when using Room D as the source is due to the TV mount being on the other side of the wall, reducing the flanking path’s effect.

Based on the calculated values, the acoustical performance of the study rooms suggests that they are not adequate for students requiring a private study space. Since they are equipped with TVs and can host group meetings, the speaker can be expected to have a raised voice. From this, the “none” degree of privacy suggests that a typical subjective response includes having a sense of community with numerous privacy complaints expected [4]. In consideration of students also wanting to use these rooms for quiet study, it is important to design and build for proper noise isolation. An approximate relationship by Weissenburger suggests that a minimum STC 52 partition should be used to have “normal” privacy, and speech not be distracting [4]. The American National Standards Institute (ANSI) similarly recommends a minimum STC of 50 when a wall assembly separates an “enclosed core learning space” from another such space [5]. These rooms are often booked for tutoring sessions, so they can be treated in a similar manner to spaces like classrooms.

## 5 Conclusion

In this scenario, it would be suggested to entirely fill the gap with a mass loaded filler designed for partitions, or similar. To conceal the television’s cables, an enclosure that fits on the back of the TV, but not inside the wall is encouraged.

Glass partitions which separated part of the room to the open plan areas were dual pane, which suggests a focus on acoustic design. Therefore, the flanking paths noticed in these rooms were likely not part of the intended design. When following a rating such as the mentioned STC 50-52, testing is encouraged to make sure an assembly performs well. In the planning stage, it is recommended to follow some sort of acoustical guideline for educational institutes specifically, such as ANSI S12.60-2002, “Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools”.

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# ACOUSTIC CHALLENGES FOR THE PACIFIC AUTISM FAMILY CENTRE

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## 1 Introduction

Autism Spectrum Disorder (ASD), a neurodevelopmental condition impacting brain development, occurs in one in 68 children [1,2]. It is characterized by difficulties in communication (verbal and non-verbal), impaired social interactions, and restricted or repetitive behaviours [1,2]. The purpose of the Pacific Autism Family Centre is to provide a single location where children and young adults can access the wide range of medical personnel and service providers required, and their families can find support. It is also meant to provide support to people researching ASD. This paper discusses the acoustic design of this facility, and compares some of the differences with more standard schools and healthcare facilities.

## 2 Project description

This building is foremost for children, teenagers and young adults, however, it is also meant to provide support to families of children with ASD, as well as provide space to further ASD research. The floor area of the building is approximately 5500 square meters, which is split over three levels. It is located ~500 m from the end of the south runway at the Vancouver International Airport, with the courtyards / play areas backing onto the Fraser River.
A large range of rooms are provided, including:

- educational spaces, e.g. group learning, music rooms, library, cafeteria and a gym/multipurpose room;
- healthcare spaces, e.g. assessment and consulting rooms, dental rooms;
- life skill spaces, e.g. activity areas, social lounge, 'digital' classroom, life skills living area (similar to an apartment, with living room, kitchen and washroom); and
- research spaces, offices, and observation rooms.

There are also a number of rooms provided specifically for people with ASD. Some examples are provided in Section 5, including 'Calm/Meeting' rooms. These are typically smaller rooms (~8 m$^2$), meant for meetings with children and parents (sometimes with privacy requirements), and also as spaces where children can 'escape' to if they become over stimulated.

## 3 Project requirements

Specific acoustic criteria did not form part of the project requirements, rather, more broadly, the facility was to incorporate sound absorbing finishes, have acoustically lined mechanical systems, and be acoustically insulated to avoid issues arising internally from aircraft noise.

Following discussions with the project team, certain rooms-spaces were identified as 'critical' (e.g. requiring a high level of sound isolation) from an acoustic perspective. A range of criteria were proposed to provide a sufficient level of sound isolation, and also to limit the internal ambient noise level and reverberation time based on these discussions, while considering the standards set out in standard school and healthcare guidelines (e.g. ANSI S12.60, UK Building Bulletin 93, The Facility Guidelines Institute Guidelines for Design and Construction of Hospitals and Outpatient Facilities).

**Figure 1:** The pacific autism family centre is located ~500m from the Vancouver international airport.

## 4 Design approach

### 4.1 Controlling external noise

Noise measurements carried out at the project site confirmed the expectation that aircraft noise would dominate the exterior noise environment. It was observed that there was an increase of ~20 dB when an aircraft flew over the site. While the frequency of these events varied, during daytime hours, there typically was an event every 3 minutes, with a duration of approximately 30 seconds. The loudest hour was from 1PM – 2PM, when the outdoor $L_{Aeq}$ was 70 dBA. The spectrum indicated a significant portion of the sound energy was at low frequencies, as expected for aircraft noise.

Multi-layer assemblies were selected for the roof and facades to provide a high level of sound isolation, particularly at lower frequencies, however, the overall performance was limited by the numerous windows throughout the building (Figure 1). A moderate-high performance glazing was selected for most spaces (6L-13-6L, STC42/OITC33). For spaces considered to be very

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noise sensitive (e.g. the calm rooms), a high performance glazing was selected (8L – 16 – 12L, STC48/OITC38). This particular glazing was also selected as it provided a good performance at the lower frequencies that dominated the external noise climate at this site.

It was challenging to accommodate this higher performance glazing since most window frames can only accommodate windows that are up to 25 mm deep (there is a limit on the low-frequency performance at this depth). Also, we learned during tendering that although the curtain wall framing selected for this project was able to accept the thicker acoustic glass (i.e. 36 mm), the doors and the opening windows could not and certain sections had to be downgraded to the STC42 option.

### 4.2 Reverberation control

Sound absorbing finishes were included throughout the building. Typically, they were in the form of acoustic t-bar ceilings, and carpeted floors. In keeping with the project requirements to limit stimulation and maintain a quiet and calm interior, where additional absorption was required, it was included more subtly, for example, by backing perforated and slotted wood with absorption (Figure 2 and Figure 3).

**Figure 2:** Slotted wood ceiling along corridor is backed with duct liner to provide acoustic absorption.

**Figure 3:** Perforated wood panels backed with duct liner on walls provide additional absorption in multi-purpose room.

### 4.3 Internal sound isolation

One of the primary drivers for internal sound isolation in this building was to ensure a reasonable level of privacy between spaces. Areas requiring low, moderate, and high levels of sound isolation were identified at the beginning of the design, and recommendations were provided to meet these objectives. By having this information and being able to provide input early on in the project, later reviews were very simple and straightforward.

Unlike some hospital projects where it is not possible to have drop-down seals due to cleaning requirements, all clinical spaces that required privacy could have full door seals.

## 5 Spaces unique to PAFC

### 5.1 Calm rooms

Six Calm/Meeting Rooms are located throughout the building. One of the primary purposes of these rooms is to provide an escape for children, where they can retreat should they become agitated or upset. An example of a situation where this room could be used may be if a child is very upset and screaming, which could in turn upset other children: a teacher or assistant may accompany this child to a calm room where they take a moment on their own to relax. The calm rooms were also used for meetings, e.g. with parents. The driving acoustical requirements were therefore high sound isolation to i) provide a private room for the children to express themselves as they need to, and ii) have confidential discussions. Vision panels (a project requirement), doors, and walls were selected to provide the required sound isolation.

### 5.2 Apartment, life skills area

One goal of PAFC is to help teens and young adults transition to independent living. To assist with this, there is a Life Skills Living area, which is similar to an apartment (it includes a living area, kitchen, laundry, and full washroom/bath area). These spaces were designed to be similar to those found in a typical home. Following from this, a limited amount of acoustic treatment was provided to approximate more typical living conditions (e.g. carpeted floors and soft furnishings, but minimal ceiling treatment).

## 6 Conclusions

It was critical to understand the uses and purposes of the various spaces in this building to ensure appropriate acoustic environments were provided. This project had the additional challenge of being located close to a busy airport. Early feedback has indicated that the end users are pleased with the acoustic design.

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# Operational Transfer Path Analysis: Practical Considerations For Selecting Sensor Positions

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## 1 Introduction

Operational transfer path analysis (OTPA) is an alternative to classical transfer path analysis (TPA) as a method used to predict the noise or vibration source/path contributions to the response of a system. While the classical TPA method uses a known input to compute frequency response functions and contributions at the receiver; the OTPA method uses operational measurable quantities to compute both the transmissibilities and the response at the receiver.

Although OTPA is currently used predominantly for vehicle noise, vibration and harshness (NVH) assessment, the method is useful for any noise and vibration assessment where a ranking of the source/path contributions is desired, e.g. industrial installations, building services installations, complex machinery and appliances, trains, aircraft, ships, submarines, construction equipment.

The goal of this paper is to introduce the underlying theory behind the OTPA method, as well as to highlight some practical considerations for selecting sensor positions during the OTPA setup and post-processing. The practical considerations are highlighted through the description of a case study and by recreating the results of the case study in a simple OTPA numerical simulation.

## 2 Background

Comparable to classical TPA, OTPA is based on a linear relationship between the source(s) and receiver(s), which can be described as:

$$\mathbf{Y}(j\omega) = \mathbf{X}(j\omega) \cdot \mathbf{H}(j\omega) \tag{1}$$

Where $\mathbf{Y}(j\omega)$ is a matrix of the output responses at the receiver measurement positions, $\mathbf{X}(j\omega)$ is a matrix of the measured quantities at input reference measurement positions (MP) and $\mathbf{H}(j\omega)$ is a matrix of the transfer functions. Important for the computation of OTPA is the setup of the matrices, where **X** and **Y** are organized such that the columns are the measurement positions (MPs) and the rows consist of blocks of measurement data.

Prior to computing the transfer function, **H**, the cross-talk (i.e. the contributions to the measurement at a reference MP from noise/vibration acting at other reference MP's) must also be minimized. This is done by a singular value decomposition (SVD) of **X**, which is also an efficient method to compute the least-squares estimate of the inverse of a matrix.

A principal component analysis (PCA) is then conducted where the lowest ranked principal components (PCs), which constitute measurement noise, are disregarded from the analysis. The result is a "noise removed and cross-talk cancelled" estimate of the transfer function matrix [1, 2, 5].

The statement "noise removed and cross-talk cancelled" should be taken with a degree of skepticism – many factors come into play which may impede the effectiveness of the cross-talk cancellation method [3 - 5], such as:

- Neglected sources/paths in the measurement setup
- Cross-coupling between input measurements
- Incorrect estimation of the transfer paths

## 2 Case study: OTPA of a road tractor

An OTPA study was conducted on an idling road tractor: Microphones were placed to cover the airborne sources and accelerometers were mounted to cover the structure-borne sources and paths. The microphone positions are shown in Figure 1, while the response measurement position was a microphone at the driver position.

The contribution analysis produced some strange results in the low frequency, specifically at 25 Hz (dominating 3rd order): The results indicated that the airborne sources were the significant contributors to the overall sound level at the response position in the tractor cab, while the structure-borne paths were insignificant contributors, at approximately 20 dB lower than the airborne contribution.

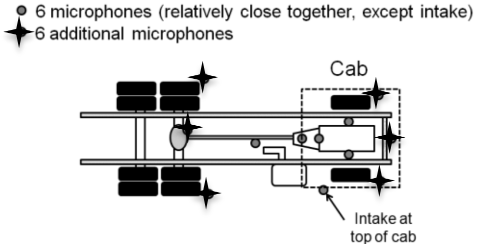

**Figure 1:** OTPA microphone positions

Given that the analysis was conducted at the engine idle operating condition (i.e. stationary), it was determined that several airborne reference MPs were not actually measuring any significant airborne sources/paths (refer to Figure 1, the MPs denoted as *6 additional microphones*). The OTPA post-processing was therefore repeated with the *6 additional microphone* MPs excluded from the analysis. The contribution analysis results indicated that the airborne and structure-borne contributions were equal. The total computed sound pressure level remained constant for both analysis cases.

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## 3 OTPA numerical simulation

To study the OTPA method with respect to the results discussed in the road tractor case study, a simplified, numerical simulation of an OTPA study was created. The purpose of the simulation was to investigate the OTPA method in a highly-controlled environment where all of the "measurement" parameters could be accurately defined.

A simple numerical simulation consisting of a source with one structure-borne path and one airborne path was created. The airborne source was modelled as a radiating spherical source of a size comparable to that of an engine, in a free field environment, and radiating a single tone at 25 Hz. Two reference microphones and one response microphone were positioned at a similar distance to the microphones for the road-tractor measurements, and one structure-borne reference MP was assumed.

The contribution analysis results indicated that an over-prediction of the airborne contribution (and under-prediction of the structure-borne contribution) occurs. The numerical simulation results represent the case where both the airborne reference MPs are at an equal distance from the source, thus they "measure" the same amplitude and phase. The calculated contribution was approximately +2.5 dB higher than the actual airborne contribution, and -3.5 dB lower for the structure-borne contribution. The total calculated response matched the actual response.

Upon review of the OTPA theory, it becomes apparent that because the reference measurements (two airborne and one structure-borne) are all fully correlated, the resulting SVD yields only one PC. When scaled, each reference MP is allotted the same contribution, and since the contribution for each path is summed, two-thirds of the contribution is presumed from the airborne path (two reference MPs, which are summed) and one-third from the structure-borne path (only one reference MP).

## 4 Discussion

The outcome of the OTPA simulation gives some insight into the likely cause of the erroneous contribution prediction that occurred in the road tractor OTPA case study: The additional microphone MPs were not actually measuring a significant additional source, and therefore were mainly measuring cross-talk (in this case, from the engine). Further, in the low frequency range it is likely that the structure-borne path is also highly correlated to the airborne path, thus the SVD does not effectively separate the contributions and the energy is simply spread out amongst the reference MPs, scaled by the relative amplitudes of the reference signals.

Recalling the potential sources of error for OTPA listed in section 2, the cause for the error in the road tractor case appears to be due to *cross-coupling between input measurement positions*. The results of the OTPA numerical simulation further support this conclusion.

The results also indicate that when two or more paths are highly correlated, and exhibit similar contributions at the response position, the number of reference MPs will influence the results: The paths will be weighted according to the number of reference MPs. In this case, PCA would show a strong contribution from very few PCs, which is an indication that the reference signals are highly correlated.

This highlights that consideration must be given to the physics when including MPs in the OTPA setup and post-processing. Particularly for airborne sources, the correct number of MPs and proper placement to ensure a good signal-to-noise ratio is critical. MPs that mainly measure cross-talk/noise (e.g. at a non-existent source), will lead to incorrect source contribution prediction results.

In general, it is proposed that the number of microphone positions used in the OTPA should be adapted according to frequency range: At low frequency (i.e. the size of the source is much smaller than one-sixth of the wavelength), the source radiates uniformly as a simple point source, thus fewer microphone positions are required; whereas at high frequency the source can be seen as a combination of multiple sources, and will therefore exhibit directivity in the radiation pattern, so several microphone positions are required to properly measure the source.

## 5 Summary and conclusion

It is important to keep in mind that the accuracy of the OTPA results depends on the correct placement and number of the sensors, and that it is advantageous to understand the system prior to setting up the measurement. A few practical considerations are summarized as follows:

- The correct number of sensors and proper placement to ensure a good signal-to-noise ratio is critical for accurate source contribution prediction results.
- The number of microphone positions per source used in the analysis should be adjusted during post-processing depending on frequency range.
- The correlation between reference measurement positions should be critically examined during the PCA.

By critically examining the OTPA data during post processing and keeping the suggestions listed above in mind, OTPA can be a convenient diagnostics tool leading to sufficiently accurate source/path contribution conclusions.

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# BLOCKING MASS FOR ARCHITECTURAL VIBRATION ATTENUATION – A CASE STUDY

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## 1 Introduction

In the modern urban environment, noise-sensitive operations are sometimes forced into close quarters with inherently noisy neighbouring tenants/owners.

This case study reports just one of the challenges associated with the retrofitting of an old theatre which was repurposed and split into two adjacent properties: a large music venue on one side, and a gaming facility on the other. Specifically, this paper addresses the continuous metal roof deck between the rooms, which is the primary noise flanking path. To help mitigate this issue, two different blocking mass solutions were designed to reduce roof deck vibration transmission. The predicted vibration attenuation is discussed, along with the two proposed designs.

## 2 Methodology

### 2.1 Description of scenario

The music venue and gaming spaces are separated by an existing demising partition, and the transmission loss is increased by the addition of a gypsum wall board (GWB) partition on the music venue-side (Figure 1). The space between serves as a crossover corridor for the music venue.

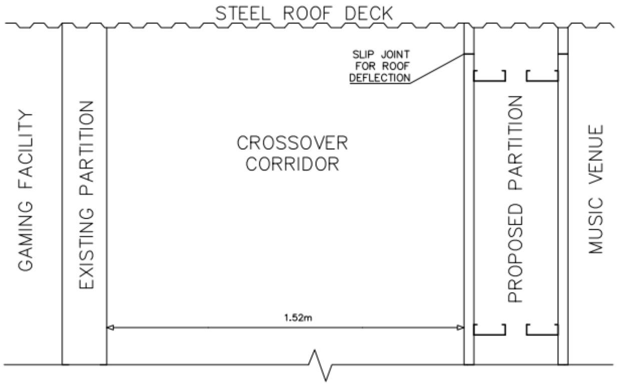

**Figure 1:** Demising partitions between music venue and gaming facility, arranged to create a crossover corridor. The proposed partition includes a slip joint designed for roof deflections.

The estimated partition transmission loss (not discussed as part of this paper) between the music venue stage and the gaming facility is such that the music noise level intruding on the gaming facility does not exceed the existing background sound level in the space, especially critical at low frequencies (125 Hz and below).

With the transmission loss through the partitions having been addressed, it is anticipated that the primary flanking noise issue is via the continuous metal roof deck (shown in Figure 1). Noise energy from the music venue excites the common roof deck, allowing vibration to travel across the demising partition and into the gaming facility, where it is re-radiated as structure-borne noise at the point of reception. As such, a blocking mass is proposed to mitigate the issue, with a target insertion loss of approximately 40 dB at 50 Hz. This targeted roof deck flanking path attenuation is based on our estimate of the partition transmission loss at low frequencies. In short, the estimate of the partition transmission loss at 50 Hz is 40 dB; as such, the goal is to offer as much sound attenuation via the roof deck flanking path as is anticipated through the partitions.

### 2.2 Calculation method

The transmission loss, $\tau$, of bending waves travelling along a plate and across a blocking mass is given in [1] as:

$$\tau = 1, \text{for } f < 0.5 f_s$$

$$\tau = [1 + f/f_u]^{-1}, \text{for } f > 2 f_s$$

$$f_s = \frac{1}{2\pi}\frac{K_1}{K^2}\sqrt{\frac{E_1}{\rho_1}};\ f_u \approx \frac{2\rho_1 {S_1}^2 K_1 \sqrt{E_1 \rho_1}}{\pi m^2}$$

$f_s$ and $f_u$ must be calculated and are functions of the steel deck's Young's Modulus ($E_1$), density ($\rho_1$), cross-sectional area ($S_1$), radius of gyration ($K_1$), mass of the blocking mass ($m$) and the radius of gyration of the blocking mass ($K$). A similar theory is given in [2]. Since the building structure exists, these variables are given and shown in Table 1.

**Table 1:** Constants used to estimate transmission loss across blocking mass.

| Variable | Description | Value |
|---|---|---|
| $E_1$ | Young's Modulus of steel | 2.00 x $10^{11}$ Pa |
| $\rho_1$ | Density of steel | 7900 kg/$m^3$ |
| $S_1$ | Cross-sectional area of steel deck | 0.00091 $m^2$ |
| $K_1$ | Radius of gyration of steel deck | 0.01033 m |

The blocking mass-related values $m$ and $K$ are dependent on the materials and geometries used, discussed in Section 3.

Assumptions made in order to implement this methodology include: 1) plate material with a "rib" blocking mass configuration; 2) full moment connection between plate and rib; 3) plate and blocking mass rib materials are the same. In practice, these could not be satisfied.

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# 3 Results

A roof deck blocking mass could be made of a row of concrete masonry unit (CMU) blocks installed directly on the rooftop, collinear with the demising partition below (Figure 2). In the case of the blocking mass being located along only one side of the plate under analysis, $K$ can be integrated and simplified to yield the following formula:

$$K = 0.333L$$

Where $L$ is the height of the blocking mass.

Assuming a CMU surface density of 341 kg/m$^2$ (per metre length of wall), calculations were undertaken showing that a row 7 courses high, weighing approximately 477.4 kg (per metre length of wall), would offer roof deck vibration attenuation of 74 dB at 50 Hz.

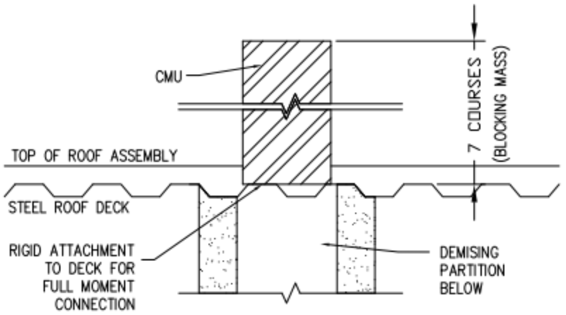

**Figure 2:** Proposed CMU blocking mass installed directly on the roof deck.

A second blocking mass design is also considered, where part of the demising wall is rigidly attached to the underside of the roof deck. In order to achieve this, the slip joint planned for the proposed double-stud partition shown in Figure 1 is moved from the interface of the wall top and roof deck, to a location "X" metres below (Figure 3).

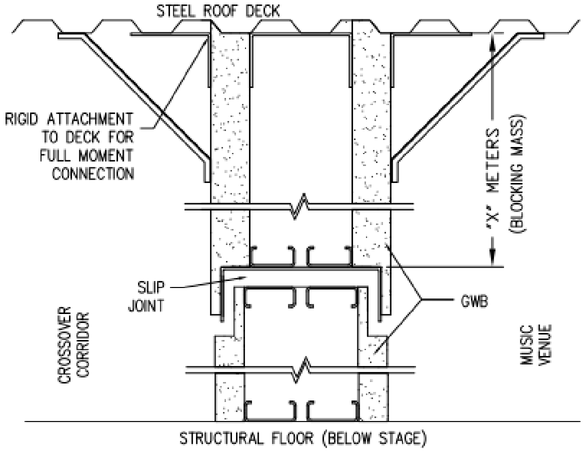

**Figure 3:** Proposed crossover corridor GWB partition with blocking mass suspended from the roof deck above.

This design decouples the top "X" metres of the partition from the rest of the partition below, effectively suspending part of the proposed crossover corridor partition from the roof deck above. Assuming a GWB density of 962 kg/m$^3$ and height of blocking mass of X = 1.75 metre, calculations similar to the CMU blocking mass were undertaken, showing that 6 layers of 16mm Type 'X' GWB per side of the blocking mass, weighing approximately 323.2 kg (per metre length of wall), offer a roof deck vibration attenuation of 70 dB at 50 Hz, approximately the attenuation achieved using the CMU block wall on top of the roof deck. Of note, this large number of GWB sheets can be reduced by using a material with a higher density, such as cement board.

At the time of writing, neither of these blocking mass designs or the crossover corridor has been built; therefore, measured data is not yet available. The intention is to measure the transmission loss of the partition and insertion loss of the roof deck blocking mass once implemented.

# 4 Discussion

The results obtained and discussed herein are considered an approximation of the actual transmission loss. Despite the assumptions made in Section 2.2, which were made in order to mathematically model this scenario, a very high transmission loss is calculated; as such, we can be satisfied with even half of the calculated transmission loss of vibrations travelling along the steel roof deck, resulting in transmission losses of approximately 35 to 37 dB at 50 Hz. With this safety factor, the calculated transmission loss is within 8-12% of the targeted attenuation; thus, the design is considered reasonable from an acoustic perspective and from a constructability perspective.

# 5 Conclusion

Blocking masses for attenuation of roof deck borne vibration have been designed and theoretically can provide high attenuation. In this case study, two proposed designs, including CMU blocks as well as a suspended GWB blocking mass as part of a demising acoustic partition, were found to be an effective, albeit theoretical way of greatly reducing noise flanking via the steel roof decks. The theoretical construction is much simpler than would be in practice, so the calculated attenuations are not expected to be realized; however, even if greatly reduced, the blocking mass designs will provide more than sufficient attenuation. Field measurements of the as-built condition, once the final design is built, will allow verification that the targeted attenuation has been achieved, and the empirical data will also allow to validate and potentially critique the modelling method described in this paper.

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# NOISE ISOLATION CLASS (NIC) TESTING OF MODULAR OFFICE PARTITIONS

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## 1 Introduction

A trend in the design of new office spaces, and the renovation of existing office spaces, is the use of modular partitions that terminate at suspended acoustic tile (T-bar) ceilings. These partitions permit office spaces to be reconfigured in the future with less effort than would be required with conventional gypsum wall board (GWB) partitions. Modular partitions, however, present challenges in terms of providing adequate acoustical privacy as they must be sealed around their perimeter joints to avoid sound leakage and there is also potential for sound to travel over the partitions via the ceiling plenum. While the ceiling plenum transmission can be addressed by selecting ceiling tiles with an appropriate ceiling attenuation class, and/or by inserting barrier elements into the plenum space, providing effective seals at the perimeter joints can be more challenging. Furthermore, modular partitions that demise offices from corridors or open-plan work areas, also require effective seals around the perimeters (including bottoms) of doors. This paper presents 2 case-studies of Noise Isolation Class (NIC) tests which highlight the challenges involved in providing acoustical privacy when using modular partitions.

## 2 NIC test methodology

For both NIC tests, a loudspeaker was used to broadcast pink noise in a corridor near the modular partitions. The loudspeaker was placed around the corner from the partition being tested, however, to avoid exposing the modular partition to the direct sound field. Spatially averaged, one-third octave band measurements were then conducted at various locations in the corridors and offices to determine the average noise levels in these spaces and the resulting NICs.

## 3 Case study 1: office building

### 3.1 Purpose of tests

Two NIC tests were conducted of a modular partition which was to form the corridor wall of a new private office. These tests were conducted on a partition which was mocked-up while construction was still in progress in order to verify that the NIC provided by the modular, corridor wall would be adequate. For the first test (Test 1), a sheet of GWB was placed against the door jamb and the resulting cavity formed between the sheet of GWB and the door was filled with insulation. Test 1 was conducted to determine the NIC provided by the modular partition while limiting the influence of noise transmission through the door. A primary goal of Test 1 was to evaluate the performance of the perimeter joint seals. For the second test (Test 2), the sheet of GWB and insulation were removed to determine the NIC that would actually be provided by the modular partition when the influence of sound transmission through the door was included.

### 3.2 Description of test partition and installation

The modular partition consisted of an extruded aluminum frame equipped with double glazing consisting of 10 mm laminated glass separated by a 75 mm airspace from a layer of 5 mm laminated glass. The partition extended horizontally between two GWB walls and extended vertically from a carpeted floor to a GWB bulkhead in the suspended acoustical tile ceiling. This bulkhead extended vertically from the acoustical tile ceiling to the structural ceiling above in order to control noise transmission via the ceiling plenum. All four sides of the modular partition were sealed to the various surfaces using PVC gazetting, referred to as “zipper seals”. A photograph of a “zipper seal” is provided in Figure 1.

**Figure 1:** Photograph of PVC “zipper” seal

The top and bottom of the partition also included aluminum “runner tracks” which were directly fastened to the floor and ceiling surfaces. Both the office and corridor sides of the wall were equipped with the zipper seal (i.e., a pair of zipper seals along each side of the wall). The cavities formed between the two sets of seals were plugged along the sides with strips of 25-mm diameter closed cell foam and filled along the top and bottom with denim insulation. The corridor door was of solid wood core construction with both perimeter and bottom seals.

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### 3.3 Results

The results were NIC 36 for Test 1 and NIC 27 for Test 2. The one-third octave band Noise Reductions (NR) obtained in the two tests are plotted in Figure 2.

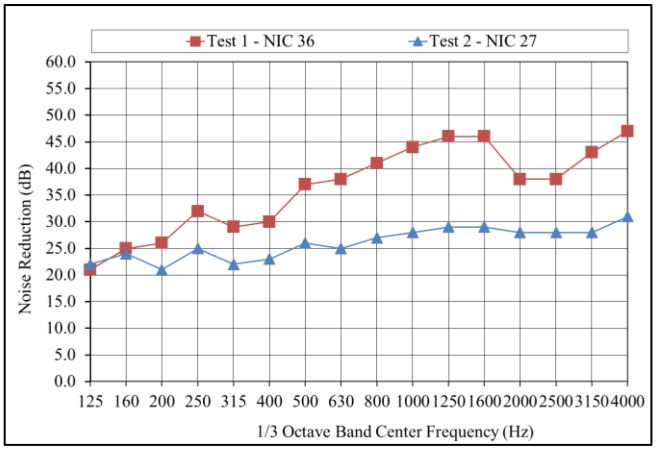


**Figure 2:** Results of case study 1 NIC testing

From Figure 2 it can be seen that including noise transmission via the door (Test 2) reduced the NR by up to 17 dB. Without the GWB sheet in place, the door was the dominant noise transmission path. During Test 1, a "listening test" did not reveal the presence of any obvious sound leakage. Furthermore, the shape of the Test 1 NR curve does not indicate the presence of any significant leakage via the seals.

## 4 Case study 2: college

### 4.1 Purpose of the tests

A series of NIC tests were conducted on a modular partition that was used as the corridor wall of an examination writing room at a college. The tests were undertaken because the acoustical privacy provided by the modular partition was considered to be inadequate by the staff and students of the college. Various measures were employed to increase the NIC of that partition and NIC tests were performed after each of the following measure were implemented:

- Test 1: initial test, no noise control measures
- Test 2: upgraded from single to double-glazing and added mechanical door bottoms
- Test 3: added 25-mm diameter closed cell foam backer rod to one of the side seals

No data was collected from Test 2 because significant sound leakage was observed at the one of the partition's side seals. The results were therefore not expected to show much improvement compared to those obtained in Test 1. The leakage was addressed prior to Test 3 through the addition of the backer rod.

### 4.2 Description of test partition and installation

The modular partition initially consisted of an extruded aluminum frame with a single layer of 6 mm tempered glass. The installation conditions of the modular partition were identical to those of Case Study 1 including the presence of a GWB bulkhead above the acoustic tile ceiling. The PVC seals used along the top, bottom and sides of the modular partition were also similar to those used in Case Study 1 although it was unclear if the cavities formed between the seals on either side of the partition were void or filled. While the door was solid core wood, it was not initially fitted with a mechanical door bottom.

### 4.3 Results

The results were NIC 19 for Test 1 and NIC 31 for Test 2. The one-third octave band Noise Reductions (NR) obtained in the two tests are plotted in Figure 3.

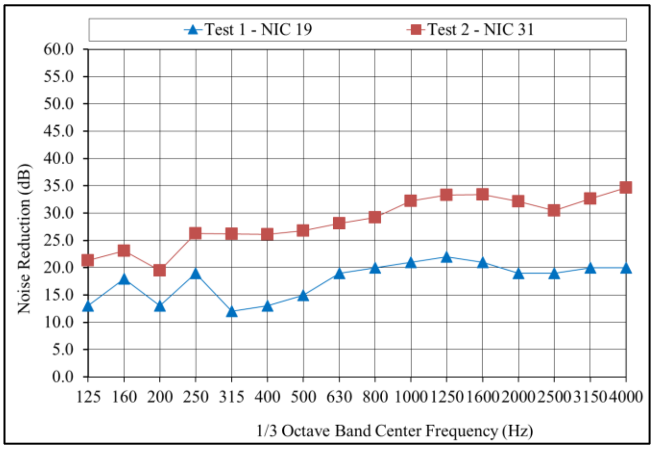


**Figure 3:** Results of case study 2 NIC testing

Referring to Figure 3, it can be seen that upgrading the glass from single- to double-glazing, installing the mechanical door bottom and plugging the side seal with backer rod increased the one-third octave band NR by up to 14 dB. Despite the addition of the mechanical door bottom, however, noise transmission via the door was still the dominant noise transmission path.

## 5 Conclusions

The results of the two case studies illustrate the limits of obtainable NICs when using modular partitions as corridor walls. However, these limits are closely related to the performance of the corridor wall door as is generally the case with more conventional GWB corridor walls. As such, when used as a corridor wall, modular partitions can provide similar acoustical performance to GWB walls (assuming the use of conventional doors rather than acoustical doors). However, when using modular partitions, special care must be taken to ensure that all potential sound transmission paths have been addressed. Of particular importance are controlling sound leakage via the perimeter seals and sound transmission over the partition through ceiling plenum. Furthermore, appropriately designed double glazing should be used when modular partitions include glazed sections.

# Abstracts for Presentations without Proceedings Paper
# Résumés des communications sans article

## Sound Transmission Loss Evaluation Of Rainscreen Wall Assemblies; Investigation Of Test Specimen Installation And Comparative Evaluation Of 54 Rainscreen Assemblies

*Maureen Connelly*

The sound transmission loss of wood-frame wall assemblies with rainscreen cavity and optional split insulation was investigated. New BC building codes and provincial guidelines requires high performance exterior wall assemblies to be designed with the incorporation of rainscreen principles; however the sound isolation performance of these wall assemblies was not addressed. Evidence from previously reported test results suggested an improved overall STC rating is expected for rainscreen wall assemblies; however, the limited data is not sufficient to predict the transmission loss of the currently mandated assemblies. In addition, during the previous evaluations of rainscreen wall assemblies the specimen under test was fully sealed, representing a face-sealed wall assembly, which does not account for the gaps in the cladding required for drainage and ventilation in a rainscreen assembly. Therefore, the prerequisite to evaluating rainscreen assemblies is a specific investigation of the design of the test specimen for acoustical measurements in three conditions: fully sealed exterior cladding, with a single drainage gap, and with a drainage and top ventilation gaps. The result of this study indicated that use of a face-seal wall test specimen to evaluate rainscreen assemblies will results in an under-estimation of transmission loss at high frequencies and critically overestimate transmission loss in low frequencies. The outcome was to include a drainage gap for the evaluation of 54 rainscreen wall assemblies with variation in exterior insulation material, exterior insulation thickness, rainscreen cavity width, cladding attachment, and cladding material layers. Overall tests results showed an expected superior behavior for fiber cement board as cladding; XPS is more sensitive to compounded variables than is rigid mineral wool in the outboard cavity; and resiliency in cladding attachments marginal increases transmission. The OITC and STC ranges over the 54 tested assemblies was 26 to 30 and 37 to 47 respectively.

## Challenges In Intelligibility Analysis Of Public Address And Emergency Notifications Systems

*Jean-François Latour*

During the past decade, there has been an increase in the requirements for Public Address and Emergency Notifications Systems (PAGA). It migrated from audibility criteria to intelligibility criteria. Checking simple charts showing sound levels at a distance is no longer enough and intelligibility must be evaluated. This task comes with several challenges as it requires more throughout inputs regarding the speakers and the spaces where the messages need to be intelligible. Also, an adequate methodology and the uncertainty in the evaluation tools are to be considered as the PAGA may be tested during commissioning and must show compliant results. Strategies to evaluate PAGA intelligibility scores are discussed along with the challenges that one could face in those kind of analysis.

## The Validation Of A Sound Intensity Imaging System For Wall Stc Calculation, With Leak Detection

*Roderick KT Mackenzie*

This paper presents a comparison study of two methods that can be used for calculating the sound transmission classification (STC) of a sample wall in a test laboratory, as per ASTM E2249-2016. In both methods, the average sound pressure level within a reverberant room is taken, and the incident sound power on the wall in the source room is calculated. In the 1st method, the traditional method of E2249, an intensity probe is swept at a constant speed, across a set path, through a wire-frame grid specially constructed for the measurement. The sound power radiating from the whole wall is then calculated from the sound intensity, and the sound transmission loss is calculated by subtracting the radiated sound power of the wall from the incident sound power. Having calculated the TL, the STC can then be calculated via ASTM E413-2016. In the 2nd method, the sound intensity probe of the I-track sound intensity imaging system is swept across the wall surface at both an irregular speed and an irregular pattern. The sound power is instantly calculated by the software, as optical tracking of the probe means the spatial and temporal sampling of the sound intensity is made automatically. The sound power is then used to calculate the STC in the same manner as the traditional method.The paper presents the precision of the two methods (traditional vs imagery). Additionally, the paper will present a secondary benefit from the use of the imagery method not available to the traditional scan method; the ability to locate and rank acoustical weaknesses within the single surface scan.

## Living Wall Noise - Case Study

*Philippe Moquin*

In a significant government building a living wall was installed as part of a major renovation. The wall is two storeys high and the upper storey opens up to two large meeting rooms. When it used for meetings the noise from the irrigation system of the living wall interferes with the speech communication of attendees. The rooms have extensive glazing and exposed natural stone walls. The ceiling is of irregular shape with acoustical treatment and the floor is carpeted. The challenge is to devise a solution that will address the noise problem as well as ensure continued health of the plants as well as the operation of the rooms and esthetics. Several measurements were performed as well as acoustical modelling to explore possible solutions. The other factor to consider in modelling is that the wall does not act as a point source but rather a series of line sources. The results of the modelling and how the measured data fits will be presented. The noise is primarily related to the flow rate of the irrigation system. An empirical derivation of noise with flow rate is about 50*log10(flow rate). The results provide one with understanding of the possible challenges of such installations and the design considerations that can help alleviate noise issues after the wall is operating.

## Using Generative Design Principles To Optimize The Acoustic Quality Of A Meeting Room

*Brady Peters, Sean Lamb*

Architecture is now designed virtually as computers have replaced traditional drafting boards. This computational space affords building designers the ability to generate numerous design options and evaluate these using performance simulation. In contrast to traditional design, where the designer directly explores the solution space, generative design involves the use of automated techniques and systems in order to refine and complete the design task. This study investigates the potentials of generative design for the optimisation of the acoustic qualities of meeting rooms. An existing meeting room is used as a case study for the generative design process. Sound quality is of critical importance in meeting rooms where clear speech communication is essential. In particular, rooms intended for speech benefit from strong early reflections of sound, low reverberation time, and low signal-to-background noise (Bradley 2003, Bradley and Yang 2009). There exists a material palette of many types of acoustic surface – absorbers, reflectors, and diffusers – and placed in different configurations these will produce different acoustic conditions. Through the organization of acoustic surfaces the acoustic qualities of rooms can be tuned (Peters 2015). Though the predominant method of acoustic control in meeting rooms and offices makes use of absorbers and reflectors, it has been suggested that diffusors may promote speech intelligibility and perception of listener envelopment (D'Antonio and Cox 2000). A recent study has shown that diffusers were beneficial in classrooms for enhancing the early arriving reflections at more distant positions and creating more uniform sound conditions (Choi 2013). In the described experiments, digital 3D models are generated in CAD through computational procedures, and these virtual 3D models are then evaluated using acoustic simulation routines. With a particular focus on rooms for speech, the described experiments study what acoustic surface configurations provide better acoustic performance. Beyond absorptive and reflective surfaces this paper investigates sound diffusing panels –how much diffusion is necessary for meeting rooms, and where to put diffusers

## Comparison Of The Acoustic Design Requirements Of The Leed, Well And Green Globes Building Rating Systems

*Jessie Roy*

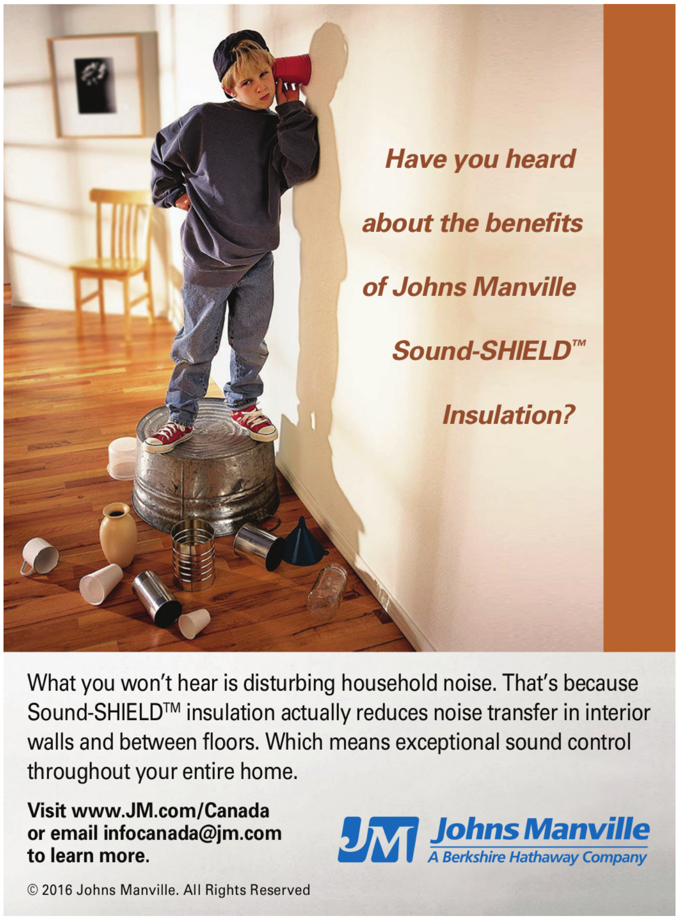
In 2005, the UC Berkeley Center for the Built Environment (CBE) published results from 34,000 building occupant satisfaction surveys collected by the center. Their study found that the area of greatest occupant dissatisfaction with LEED and other green buildings was acoustics, and that the degree of dissatisfaction with acoustics was greater for these buildings than in conventional buildings. Since its release, the CBE study, and others like it, have helped to drive the incorporation of acoustic requirements into North American green building rating systems for a variety of building types. This paper will provide an overview of the acoustic prerequisites and optional performance targets of the latest versions of the LEED, WELL, and Green Globes green building rating systems. It will compare the acoustic performance requirements of these rating systems, and provide comment on key design considerations for achieving these requirements.

### Broadband Acoustic Energy Confinement In 3d Printed Hierarchical Sonic Crystals

*Amir Shakouri, Zheng Fan*

The application of additive manufacturing (3D printing) for developing novel sonic crystals is discussed by studying an example of Hierarchical Sonic Crystal (HSC). Fused Deposition Modeling (FDM) additive manufacturing has been employed for rapid prototyping of this structure from Acrylonitrile Butadiene Styrene (ABS) plastic. Finite Elements Method (FEM) has been applied for designing the HSC using band structure analysis. Acoustic measurements are conducted on the sample in a direct field inside an anechoic room. The details of the acoustic experimental setup are discussed and the experimental results are compared with the FEM results. It is shown that HSC is capable of confining acoustic energy over a broad frequency range and at multiple lattice points. The potential application of the HSC for acoustic energy harvesting is discussed.

# BIOMEDICAL ACOUSTICS AND ULTRASOUNDS - ACOUSTIQUE BIOMÉDICALE ET ULTRASONS



# AN IMAGE-GUIDED FOCUSED ULTRASOUND SYSTEM FOR GENERATING ACOUSTIC SHOCK WAVES THAT INDUCE TRAUMATIC BRAIN INJURY IN WILD-TYPE ZEBRAFISH

**Graham A. Ferrier[*1], Rajwinder Kaur[†1], Eugene Park[‡2], Elaine Liu[♯2], Andrew J. Baker[◊2, 3] and Jahan Tavakkoli[♠1, 4]**
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[2]Li Ka Shing Knowledge Institute, St. Michael's Hospital, Toronto, Ontario, Canada.
[3]University of Toronto, Ontario, Canada.
[4]Institute for Biomedical Engineering, Science and Technology, Toronto, Ontario, Canada

## 1 Introduction

Unintentional injuries such as traumatic brain injury (TBI) are the leading killer and disabler of Canadians under the age of 44 [1]. TBI is induced by biomechanical forces caused by a direct blow to the head, face, or elsewhere on the body with an impulsive force transmitted to the head, yielding a rapid but short-lived impairment of neurologic function [2].

In order to investigate TBI mechanisms, we have developed an image-guided focused ultrasound system that generates acoustic shock waves to induce TBI in wild-type zebrafish. This system permits the development of a TBI model for zebrafish that adequately recapitulates mild (closed-head) traumatic brain injury and subsequent secondary injury mechanisms. Acoustic shock waves of short pulses (pulse length = 50 ms) of intense focused ultrasound (pressure = 11 MPa) within a 7.5 mm × 1.2 mm focal zone cause brain injury by inducing mechanical stress and transient cavitation. Since zebrafish have a high degree of genetic homology and cell signaling pathways relative to mammalian species, this research may provide insight into shockwave-induced dysfunction leading to TBI and disruption of the blood-brain barrier in humans.

## 2 Method

This shock wave generation system incorporates a 1 MHz focused ultrasound transducer (focal length = 10 cm in water), which is excited by pulsed 1 MHz signals that are amplified and transmitted via an impedance-matching transformer. A calibrated radiation force balance is used to correlate input electrical power with output acoustic power, which is subsequently correlated with focal-zone pressure using measurements from a calibrated hydrophone. In our system, the output acoustic power is approximately 64% of the input electrical power [3].

Focal-point acoustic intensities and pressures are simulated using a Linear Acoustic and Temperature Simulator (LATS) program developed by our group [4]. LATS simulates the axial and cross-sectional acoustic intensity profiles (Fig. 1) for a given transducer geometry and input power. Corresponding calculated acoustic pressures reveal good agreement between the simulated and measured acoustic pressures (Fig. 2). The profiles also provide insight into the intensity distributions and beam-widths at various distances from the transducer.

An imaging probe embedded within the focused transducer generates confocal B-mode images (Fig. 3) to enable visualization of the zebrafish location, and to locate the zebrafish brain consistently within the focal zone.

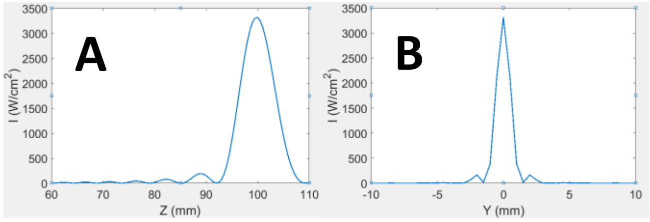


**Figure 1:** A) Axial and B) cross-sectional intensity profiles.

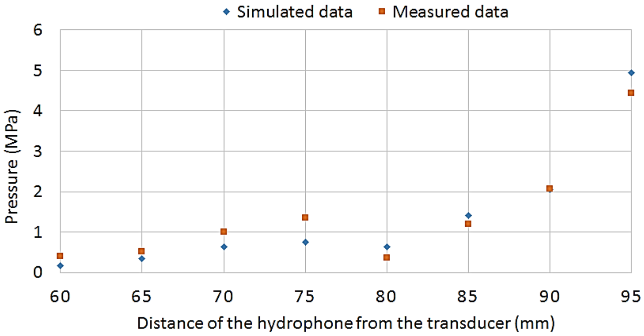
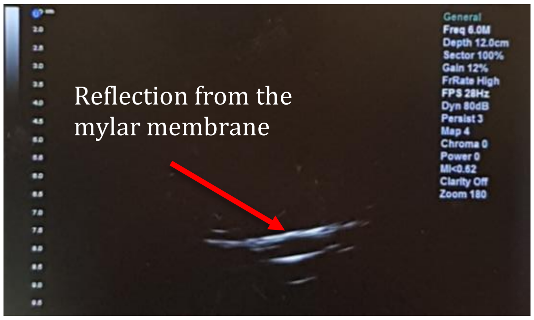


**Figure 2:** Simulated and measured acoustic pressures vs. distance from the transducer.



General
Freq 6.0M
Depth 12.0cm
Sector 100%
Gain 12%
FrRate High
FPS 28Hz
Dyn 80dB
Persist 3
Map 4
Chroma 0
Power 0
MI<0.62
Clarity Off
Zoom 180

**Figure 3:** Confocal B-mode images enable visualization of the zebrafish location. When the zebrafish head is aligned with the imaging transducer, gill movement is visible in the B-mode image.

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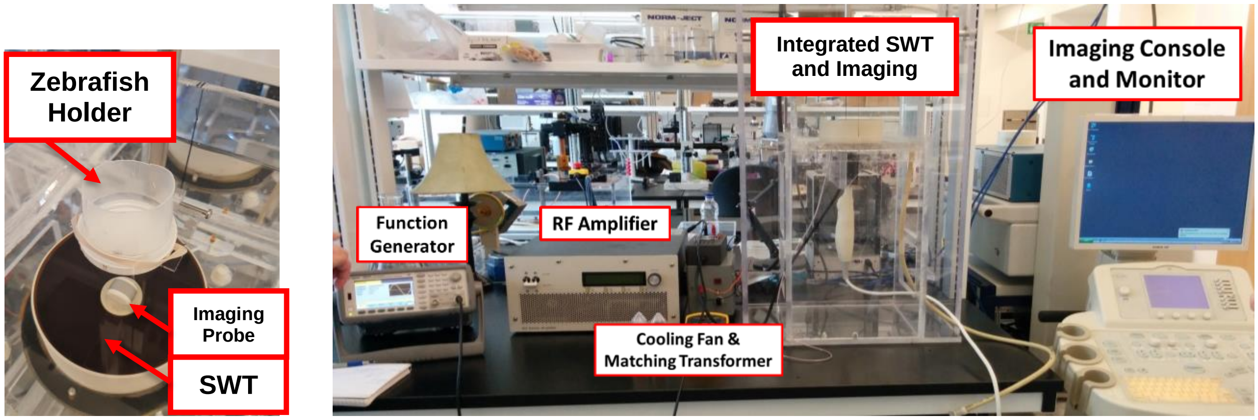

**Figure 4:** Left, zebrafish holder positioned at the focal length of the shock wave transducer (SWT). Right, full image-guided focused ultrasound system.

Zebrafish are anaesthetized using 100 ppm clove oil, and then individually positioned in a holder within a water tank (Fig. 4). The holder contains a 3 mm hole covered by a thin layer of ultrasound-transparent mylar membrane, which is located under the zebrafish head to ensure that acoustic shock waves are delivered only to the head.

## 3 Impact on zebrafish

In our previous post-TBI studies, zebrafish shocked with 50 ms pulses of 11 MPa typically experienced longer recovery times, decreased swim distances and velocities, heightened anxiety, and altered group social dynamics [5]. However, after injection of neuroprotective compounds such as CB3 and SD1 into shocked zebrafish, preliminary results indicate that these compounds can yield a reversal of the symptoms experienced by shocked zebrafish.

CB3 and SD1 have an additive effect on increasing swim distance, lowering anxiety, and increasing the mobility of shocked zebrafish. For instance, control fish explore the tank floor for ~60 s before swimming near the surface (Fig. 5a), and shocked fish explore the tank floor for significantly longer (> 200 s) before swimming near the surface (Fig. 5b). Adding CB3 (Fig. 5c) and then SD1 (Fig. 5d) are found to induce the shocked fish to swim at shallow depths after times comparable to the control group (~60 s).

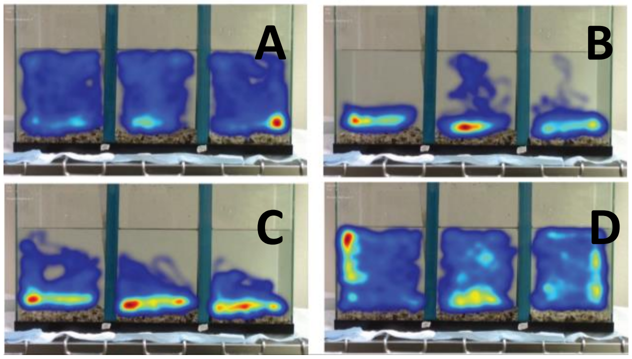

**Figure 5:** Heat maps representing the swim coverage of zebrafish in water tanks under various conditions: A) Control; B) Shocked; C) Shocked and injected with CB3; D) Shocked and injected with CB3 and SD1.

## 4 Conclusion

An image-guided ultrasound system has been developed to deliver acoustic shock waves effectively to induce TBI in zebrafish. Proper alignment of the zebrafish with the shock wave transducer can be checked using confocal B-mode imaging. Simulated and measured acoustic pressures are found to be in good agreement. Zebrafish shocked with a 50 ms shock wave at 11 MPa exhibit longer recovery times and exhibit erratic swim patterns when compared to those of control fish. Further investigations on the impact of neuroprotective compounds will be conducted with this system to gain insight into the mechanisms of TBI.

## Acknowledgments

The authors acknowledge research funding support from the Ontario Research Fund - Research Excellence (ORF – RE) and the Ryerson Dean's Research Fund.

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# Evaluation Of The Bias On X-Ray Absorptiometry And Quantitative Ultrasound Measurements Due To Bone-Seeking Elements

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## 1 Introduction

Dual-energy x-ray absorptiometry (DXA) is the current clinical gold standard of bone mineral density (BMD) estimation for the diagnosis and monitoring of osteoporosis. DXA measures areal bone mineral density (aBMD) based on the difference in x-ray photon attenuation between bone and surrounding soft tissue. Substitution of calcium (Ca, Z = 20) with bone-seeking elements such as strontium (Sr, Z = 38), lead (Pb, Z = 82) and aluminum (Al, Z = 13) can change the overall photon attenuation of bone, and can result in inaccurate estimations of aBMD [1].

Quantitative ultrasound (QUS) is an alternative bone densitometry technique that estimates BMD based on broadband ultrasound attenuation (BUA) and speed of sound (SOS) measurements. A derived quantity termed the stiffness index (SI) is calculated from BUA and SOS, and it is converted to yield an estimated BMD [2].

The objective of this study was to use bone-mimicking phantoms that contain strontium, lead or aluminum to assess the effect of the bone-seeking elements on DXA and QUS measurements.

## 2 Method

### 2.1 Production of bone-mimicking phantoms

Hydroxyapatite (HA) phantoms that are equivalent to bone mineral were synthesized using the method developed by Da Silva *et al.* [3, 4]. Seven HA phantoms that contain varying molar percentages of strontium [Sr/(Sr+Ca)] ranging from 0 to 2% were produced. In case of lead and aluminum, five HA phantoms that contain varying concentrations of the elements ranging from 0 to 200 ppm were produced for each element.

To produce bone mimicking phantoms, finely powdered HA phantoms were mixed with 5% *w/w* porcine gelatin solution [5]. The mixtures of gelatin and HA were poured into a container with the dimension of 6.5 cm x 6.5 cm x 2.5 cm to yield constant volumetric BMD (vBMD) of 200 mg/cm$^3$.

### 2.2 DXA measurements

aBMD of the constructed bone-mimicking phantoms were assessed using Hologic Horizon® DXA. The phantoms were submerged in water to simulate soft tissue that surrounds bone. Each phantom was measured ten times and was repositioned between each measurement.

### 2.3 Clinical QUS measurements

BUA, SOS and SI of the bone-mimicking phantoms were measured using Hologic Sahara® QUS device. The phantoms were placed in an acrylic box with a thin Mylar window. The box was filled with castor oil to eliminate air gaps and to simulate soft tissue. Each phantom was measured five times and was repositioned between each measurement.

### 2.4 In-house research QUS measurements

Additional QUS measurements were obtained using an in-house research system. The in-house research QUS system consisted of two 1 MHz transducers that are placed 20 cm apart, and the transducers were submerged under de-gassed and deionized water. The trabecular bone-mimicking phantom housed in the acrylic box with the castor oil filler was placed in the middle of the two transducers for measurements. Each phantom was measured five times and was repositioned between each measurement.

## 3 Results

The measured parameters were plotted as a function of concentration of strontium, lead and aluminum in Figure 1, 2 and 3, respectively. As shown in Figure 1, a strong linear relationship was observed between aBMD and strontium concentration ($r$ = 0.995, $p$ < 0.001). However, no statistically significant relationship ($p$ > 0.05) was observed between aBMD and lead or aluminum concentrations.

Furthermore, no statistically significant relationship was found between all parameters measured by clinical QUS and strontium or aluminum concentrations. In the case of clinical QUS, BUA was found to vary linearly with lead concentration, ($r$ = 0.899, $p$ < 0.038). However, no statistically significant changes were observed for SOS or SI.

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For the research QUS system, no statistically significant correlations were observed for all three parameters in relation to all the bone-seeking elements.

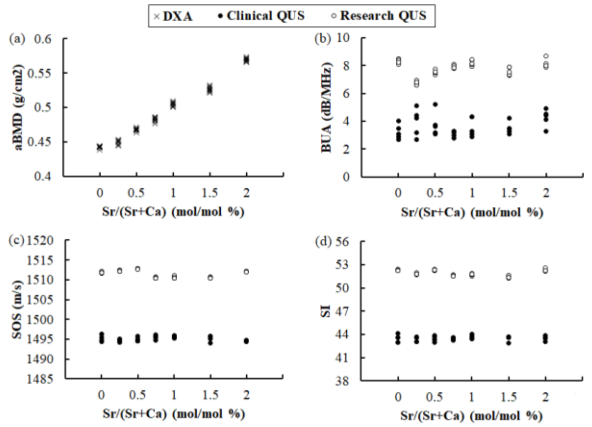

**Figure 1:** (a) aBMD measured by DXA, (b) BUA, (c) SOS and (d) SI measured by clinical and research QUS systems with respect to strontium concentration in mol/mol%.

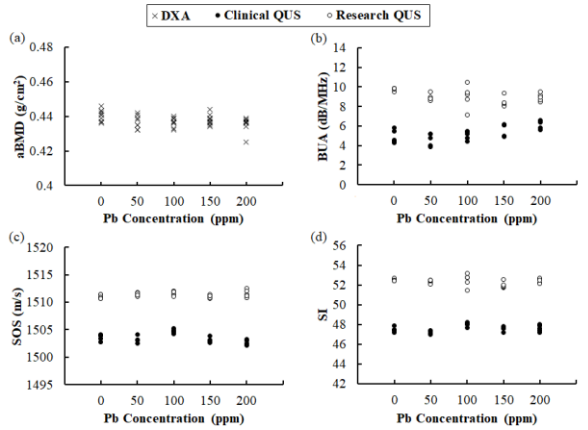

**Figure 2:** (a) aBMD measured by DXA, (b) BUA, (c) SOS and (d) SI measured by clinical and research QUS systems with respect to lead concentration in ppm.

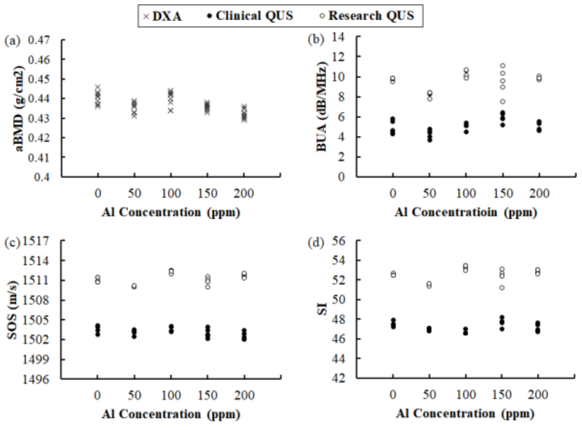

**Figure 3:** (a) aBMD measured by DXA, (b) BUA, (c) SOS and (d) SI measured by clinical and research QUS systems with respect to aluminum concentration in ppm.

## 4 Discussion

The observed strong linear relationship between aBMD and strontium concentration was consistent with previous studies [1]. In case of lead and aluminum, although a bias in aBMD was expected, the clinically relevant concentrations of the two elements were too low to induce significant deviation in the aBMD measurements.

Although there was a linear correlation between BUA and lead concentration, it should be noted that SI did not undergo statistically significant change under clinically relevant concentrations. This was observed for all three elements. Since SI is the basis for the BMD estimation of the QUS system, these results suggest that the estimation of BMD by QUS is not influenced by the clinically relevant concentrations of strontium, lead or aluminum.

## 5 Conclusion

This study demonstrates that strontium substitution of calcium can induce overestimation of aBMD, as previously reported, when measured by DXA. In contrast, QUS measurements were independent of the strontium concentration. In addition, clinically relevant levels of lead and aluminum do not seem to influence DXA and QUS measurements.

## Acknowledgments

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# FREQUENCY-DOMAIN SYNTHETIC APERTURE FOCUSING TECHNIQUES FOR IMAGING WITH SINGLE-ELEMENT FOCUSED TRANSDUCERS

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## 1 Introduction

Synthetic aperture focusing techniques (SAFT) make the lateral spatial resolution of single-element conventional B-mode imaging more uniform, which leads to an improved spatial resolution and an extended depth of field. SAFT uses signal processing techniques to synthesize a larger aperture by moving a smaller physical aperture. Several SAFT algorithms have been proposed for different transducer geometries. For single-element focused transducer, the virtual point source techniques have proposed, which treats the geometric focus of the transducer as a virtual point source in the image reconstruction process [1].

In this work, we proposed two frequency-domain SAFT algorithms that are based on 2D matched filtering technique. The first algorithm is called virtual source FD-SAFT (FD-SAFT-VS), which is similar to the algorithm presented in [2] that was implemented for flat circular transducers. However, FD-SAFT-VS treats the focal point of the transducer as a virtual flat circular source. The second algorithm is called deconvolution FD-SAFT (FD-SAFT-DE), which uses the simulated point-spread function (PSF) of the imaging system as a filter kernel for the matched filter in the image reconstruction.

### Frequency-domain virtual source SAFT (FD-SAFT-VS)

The recorded echo signal can be expressed in frequency-domain as a convolution model as [2]:

$$S(k_x,\omega) = \alpha \cdot A(k_x)\cdot \omega^2 H(\omega)\cdot F(k_x,k_z),$$

where $k_x$ and $k_z$ are wavenumbers in lateral and axial directions, respectively, $\omega$ is the angular frequency, $\alpha$ is a constant coefficient, $A(k_x) = \mathrm{jinc}^2(k_x a)$ is the directivity function for a flat circular transducer, $a$ is the radius of the transducer, $H(\omega)$ is the transmit and receive electro-mechanical impulse response of the transducer, and $F(k_x,k_z)$ is the object's reflectivity function.

The goal of FD-SAFT image reconstruction is to get a better representation of $F(k_x,k_z)$. FD-SAFT-VS splits the recorded data into pre-focal and post-focal regions and image reconstruction is carried out separately in each region. In the pre-focal region, the recorded data, the electro-mechanical impulse response and the excitation pulse are flipped in the axial direction prior to performing fast Fourier transform (FFT). However, in the post-focal region, the recorded data, the electro-mechanical impulse response and the excitation pulse are transformed into Fourier domain without flipping. The image reconstruction is carried out in the pre-focal and post-focal regions as following:

$$\hat{F}(k_x,k_z) = \mathcal{S}^{-1}\left\{\exp\left[j\left(\sqrt{4k^2-k_x^2}-2k\right)z_c\right]\cdot A^*(k_x) \cdot \omega^2 H^*(\omega)\cdot P^*(\omega)\cdot S(k_x,\omega)\right\},$$

where $z_c$ is the perpendicular distance from the transducer to the midpoint of the ROI, $k$ is the wavenumber, and the asterisk represents complex conjugate. $\mathcal{S}^{-1}\{\cdot\}$ is the Stolt transformation, which transforms $(k_x,\omega)$ into $(k_x,k_z)$ coordinates defined by: $k_z(k_x,\omega) = \sqrt{4k^2-k_x}$ (for details see [3]). Finally, inverse FFT is performed to pre-focal and post-focal regions and then pre-focal region is flipped in the axial direction to its original orientation before joining it with the post-focal region to get the final reconstructed image.

### Frequency-domain deconvolution SAFT (FD-SAFT-DE)

If the ultrasound image formation is assumed to be based on the convolution model, then an image, $S(k_x,\omega)$, can be modelled as a convolution of the system's PSF, $PSF(k_x,\omega)$, and object's reflectivity function, $F(k_x,k_z)$ in frequency-domain as following:

$$S(k_x,\omega) = F(k_x,k_z)\cdot PSF(k_x,\omega).$$

The *PSF* represents the response of the system to a point scatterer and it takes into account all the characteristics of the imaging system. However, the *PSF* depends on the position between the transducer and point scatterer. For a single-element focused transducer, the *PSF* at the focal point of the transducer is distorted the least because the diffraction effect at that position is minimal.

FD-SAFT-DE performs the image reconstruction by deconvolving the simulated *PSF* of the system from the recorded echo data via matched filtering, and then followed by Stolt transformation, as:

$$\hat{F}(k_x,k_z) = \mathcal{S}^{-1}\{PSF^*(k_x,\omega)\cdot S(k_x,\omega)\}$$

## 2 Method

The performances of the proposed algorithms were evaluated using simulated radio-frequency (RF) data. The simulated data were generated using Field II simulation software [4] and the simulated transducer was a commercially-available single-element spherically focused with 25 MHz central frequency, 7 mm diameter and 15 mm

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focal length (RMV-710B, FUJIFILM VisualSonics Inc., Toronto, Canada). The electro-mechanical impulse response of the transducer was determined experimentally. The values of the simulation parameters are shown in Table 1. The medium consisted of water with several point scatterers at different axial distances. White Gaussian noise, mimicking electronic noise, was added to the generated RF data, where its magnitude and spectrum were set to match the RF data that was recorded experimentally. The performances of the proposed algorithms were compared to the conventional B-mode. The contour area of each point scatterer from the reconstructed images was measured at -6 dB for the quantification of the spatial resolution and at -18 dB for the quantification of the side lobes. Electronic signal-to-noise ratio (SNRe) of each point scatterer was also measured similar to ref. [5].

**Table 1:** Values of the simulation parameters.

| **Parameter** | **Value** |
|---|---|
| Speed of sound | 1540 m/s |
| Attenuation | 0.0022 dB/(cm.MHz) |
| Sampling frequency | 420 MHz |
| Excitation pulse | 1 cycle sinusoidal wave |

## 3 Results

The reconstructed images of the conventional B-mode, FD-SAFT-VS and FD-SAFT-DE of the point scatterer in water are shown in Figure 1. The measurement of contour area at -6 dB and -18 dB levels, and SNRe of each point scatterer from the reconstructed images are shown in Figure 2.

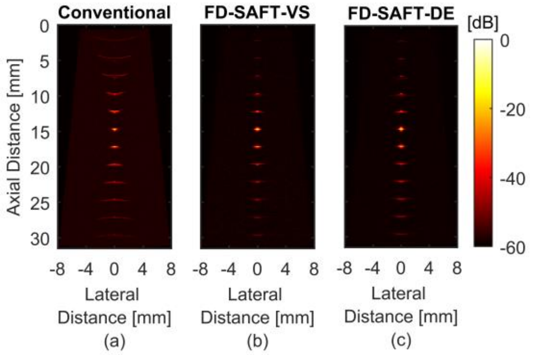

**Figure 1:** The reconstructed images of the point scatterer phantom in water. The conventional B-mode (a), FD-SAFT-VS (b), and FD-SAFT-DE (c) are shown.

## 4 Discussion

As shown in Figure 2, the conventional B-mode had the largest areas of the contour at both -6 dB and -18 dB and the contour areas decreased around the focal distance of 15 mm. FD-SAFT-DE had smaller contour areas compared to the conventional B-mode. In addition, FD-SAFT-VS had generally the smallest contour areas. Thus, both SAFT algorithms were able to extend the depth of field beyond the conventional B-mode. The reason for these improvements is that the FD-SAFT-VS and FD-SAFT-DE compensate for the diffraction effects, the electro-mechanical impulse response and the excitation pulse of the transducer. Furthermore, the SNRes of all methods were highest at the focal distance and they decreased away from the focal distance. FD-SAFT-VS and FD-SAFT-DE had higher SNRes compared to the conventional B-mode by an average of 3.62 dB and 5.35 dB, respectively.

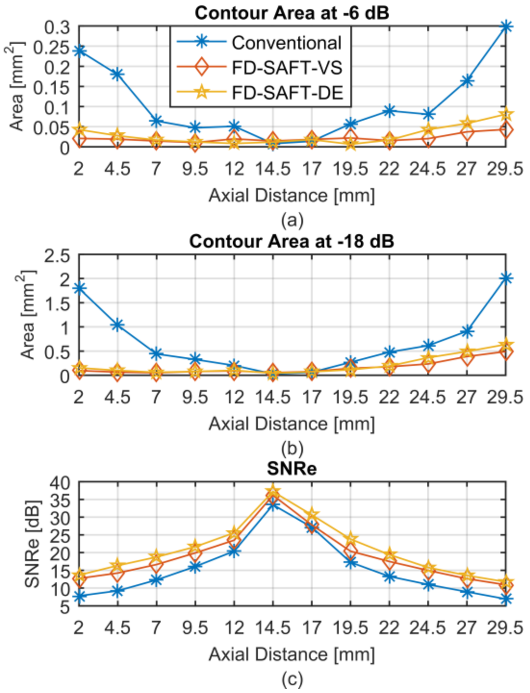

**Figure 2:** The measurements of the contour area at -6 dB (a) and -18 dB (b), and measurement of the SNRe (c).

## 5 Conclusion

Among the methods studied, the FD-SAFT-VS had the smallest spatial resolution and the FD-SAFT-DE had the second smallest spatial resolution. In addition, the FD-SAFT-DE generally had the higher SNRe compared to other methods. Thus, the proposed methods made the spatial resolution more uniform and extended the depth of field of conventional B-mode ultrasound imaging.

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# EDUCATION IN ACOUSTICS - FORMATION EN ACOUSTIQUE

# TEACHING ACOUSTICS IN ARCHITECTURAL PROGRAMS IN CANADA

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## 1 Introduction

This paper aims to reflect, based on experience of the author, on the way in which acoustics is taught to Canadian architectural students. A few years ago, the author faced the challenge to innovate the III-year undergraduate acoustics course at Ryerson University. The goals of this course, named "Light/Sound in Architecture" (ASC521), are "*to develop a basic understanding of lighting and sound, and to become familiar with the primary modes of characterizing and quantifying light and sound in engineering terms. Basic design concepts and techniques used to manipulate and control sound and light in buildings will be explored*."

The process of updating the teaching approach and the contents of this course started with the analysis of other similar courses offered in Canada. Currently, there are 11 university schools of architecture which have been granted CACB Accreditation in Architecture. Based on the information available on the websites of these programs, the analysis showed that while the Architectural Science program at Ryerson University, as well as some other institutions, included into a single course the contents of lighting and acoustics, many programs ignore the subject of acoustics in a specific manner (Table 1). The common reason behind this decision is the lack of a faculty member with an expertise in acoustics or the other competitive requests to get the accreditation of their programs, which do not leave space for a dedicated course about acoustics.

This situation is probably known and no surprising; in fact, a NSERC CREATE application was submitted a couple of years ago with the title "Training Program for Acoustical Synthesis in High Performance Buildings and Communities" to increase to attention towards architectural acoustics in Canadian universities (unfortunately, it was not funded).

## 2 Acoustics at Ryerson architectural school

In order to understand some of the characteristics and constrains of the course ASC 521, it is useful to point that this course consists of 12 lectures offered once a week for 3 hours each. ASC 521 dedicates six classes to acoustics (and six to lighting), a surely short time to deliver its content properly and deeply. In fact, through the course ASC521, students should become familiar with basic laws of sound propagation in rooms, as well as the design criteria and analysis procedures for the acoustic design of performance spaces. Typically the course is taught in large classrooms (theaters) given the over 100 students attending it.

**Table 1:** Acoustic courses in Canadian architectural schools

| School | Program Name | Acoustics course |
|---|---|---|
| University of British Columbia | Masters of Architecture | ARCH 531 - Architectural Technology II |
| | more courses in Mechanical and Civil Engineering | MECH 405 - Acoustics and Noise Control<br>MECH 505 - Industrial and Environmental Acoustics and Vibration<br>MECH 584 - Advanced Engineering Acoustics<br>PHYS 318 Acoustics |
| University of Waterloo | Bachelor of Architectural Studies | ARCH 272 - Interior Environments: Acoustics and Lighting |
| Universite de Montreal | Bachelor of Science in Architecture | ARC 5317 - Lighting Engineering and Applied Acoustics |
| Carleton University | Bachelor of Architecture | *ARCN 3003 - Theatre Production* |
| Dalhousie University | Master of Architecture | ARCH 5208 - Acoustics |
| McGill University | Master of Architecture | ARCH 555 - Environmental Acoustics |
| *Athabasca University* | *Post-Baccalaureate Diploma in Architecture* | ARCH 526 - Architectural Design: Acoustics |

One of the elements that emerged in teaching this course is the somehow limited attention of students who believe that in an architectural program, the no-studio courses would deserve less attention than design courses. In the case of subjects such as acoustics, which is perceived as an engineering discipline with strong bases into physics, students also consider the course far from the architectural profession. As a result, new pedagogical approaches were introduced to enhance students' participation.

The course has been traditionally based on describing room acoustics using photos and graphs, while a visit to a notable performance space allowed students to give the spatial sense of a room, but often it failed at providing the experience of listening the different acoustic attributes of a space. It was believed that the possibility to compare different sound spaces using auralizations would have allowed students to get better experiences.

Some novelties were hence introduced in ASC 521 over the last few years: students had to visit and describe both architecturally and acoustically a performance space, then a room acoustic simulation was run during a lecture in class to show some of the challenges of the acousticians' profession [1], and finally, sound level measurements were done.

A Ryerson Learning Teaching and Education Fund grant allowed to develop new ways for teaching acoustics. The project epitomized the ambition of Ryerson University

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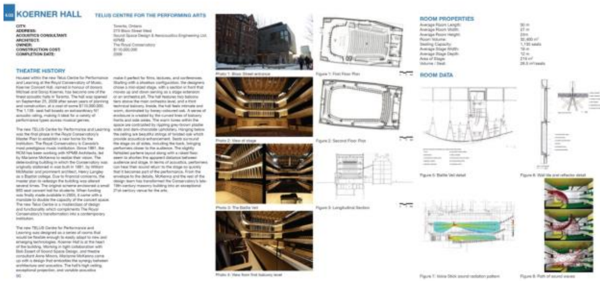
towards applied learning while constantly innovating its offerings in blended learning environments through creating immersive virtual acoustic experiences. In fact, while a great deal of emphasis is placed upon the visualization of space during the design, yet the acoustics of a space is often poorly considered by architects. Based on the architectural data provided by the students (Fig. 1), the author aimed at creating a repository for collecting and sharing acoustic data about performing spaces, such as impulse responses and auralization. This intent aimed to enable students to explore room acoustics beyond class hours and to create a new way to experience a room by allowing to listen to auralizations done in different halls. Since the intent is that this large data source will grow in the following years, it was decided to collect all the data into two open-source e-books which to showcase the acoustics of main Canadian performing spaces (Fig. 2). Once the impulse response collection and the auralizations will be completed done, it will be possible to conduct a virtual trip in many Canadian performance halls.


KOERNER HALL

TELUS CENTRE FOR THE PERFORMING ARTS

THEATRE HISTORY

ROOM PROPERTIES

ROOM DATA

**Figure 1:** Example of the concert halls description in the e-book.

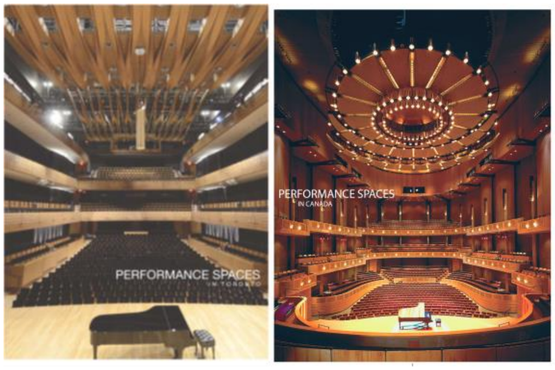


**Figure 2:** Covers of the e-books including 70 performing halls.

The intended e-books will also offer the possibility to listen to different sounds in the same space, allowing to understand the importance of performing a given music in a space with a particular acoustics, being more experiential leaning that the technical validation of sound formulas.

Another important novelty in ASC 521 was represented by the introduction of the use of smartphones into the teaching delivering. Smartphones have evolved into powerful computing machines with exceptional capabilities and many built-in sensors. Meanwhile, smartphone developers now offer many sound measurement applications (apps). This allowed to base two course assignments on measurements done in real life environments with dedicated apps. Recent studies have compared and examined available sound recording apps for smartphones, and have found that some apps, such as SoundMeter give good results [2]. Without doubting that accurate sound measurements would need to be conducted using professional sensors, but for the sake of practicality (given the over 100 students attending ASC521), students were asked to use their smartphones for assignments such as: "*in pairs, after having downloaded on your smartphones at least two apps each, conduct measurements of different urban sound environments (with different average sound pressure levels), and discuss the sound level results of the different apps.*" Students could hence figure out common sound pressure levels but also inconsistencies of their devices as they became aware of the limits of these apps and of the importance of detailing reporting and professional writing (Fig. 3).

**Figure 3:** Samples of the submitted assignment with app measures.

## 3 Educational opportunities and challenges

Many questions raised from the first experiences about introducing new educational approaches in acoustic teaching. First of all, about the possibility for smartphone apps to replace a professional measuring devices and about how much these apps should be included in our teaching. The results proved that sound pressure level measurements were poorly detected with smartphones. Comparing different apps on the same or on different smartphones resulted in significant fluctuations of the measured values. This means that smartphone apps are not very reliable, although they represent a resource for enhancing students' participation and engagement beyond class hours. The limits of the app force to rethink their values in order to build a more scientifically valid exercise.

Finally, the e-books that have been created still include few rooms, and hopefully with the support and donation of Canadian acousticians, more impulse responses will be collected in the future.

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# ACOUSTICS SPECIALIZATION FOR BUILDING ENGINEERS

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## 1 Introduction

The Department of Building, Civil and Environmental Engineering at Concordia University offers undergraduate and graduate acoustic courses for students who want to pursue a career in architectural acoustics. This paper describes an overview of the architectural acoustics specialization program, the acoustics curriculum for building engineers, lab facilities, and research areas developed at Concordia University. The program guides students to gain fundamental knowledge in acoustics and analysis skills of indoor environments to achieve optimal acoustic performance in buildings. The acoustic courses cover topics from acoustic principles to professional applications in room acoustics and noise control methods.

The building engineering program at Concordia University is designed to encompass the body of knowledge pertaining to all aspects of a building with an understanding of their impact on the environment including acoustics. The building engineering program at Concordia started in 1977. The Department of Building, Civil and Environmental Engineering is located at Sir George Williams campus in Montreal, QC. Currently, there are 40 tenured (or tenure-track) professors and 4 part-time affiliated professors in the department. The department provides Bachelor of Engineering (BEng), Master of Applied Science (MASc), Master of Engineering (MEng) and Doctor of Philosophy (PhD) degrees in building engineering. There are approximately 350 undergraduate and 300 graduate students in the program. The program at Concordia is the only building engineering program, which is accredited by the Canadian Engineering Accreditation Board (CEAB).

## 2 Acoustic curriculum at Concordia

The building engineering program at Concordia currently offers two acoustic courses for students and two additional courses are offered by other departments in the faculty of Engineering and Computer Science. Brief course descriptions and teaching strategies for each course are as follows.

### Acoustics and lighting

The Acoustics and Lighting (BLDG366) course is a core course for junior level students in the building engineering program. The course provides fundamental knowledge in acoustics and key design principles for acoustically sensitive spaces. Laboratory experiments and design projects are essential components of this course for students' engagement. The main objectives of this course are:

1) understanding fundamental aspects of sound, hearing, acoustic measurement device and architectural acoustic design practices,
2) attaining the competence to solve complex acoustic problems by using measurement data and theoretical calculations,
3) and presenting acoustical design strategies with clarity and professionalism.

In this course, the students acquire skills in four CEAB attributes; investigation, use of engineering tools, professionalism and impact of engineering on society and the environment. For building engineering major students, the most important aspect of teaching strategy is disseminating significance of acoustics in building design. Sharing daily experiences about acoustic quality in space are highly encouraged in the class and through a social networking service like Twitter. Audio samples are the valuable resource as students learn theories more effectively when they can hear the acoustics. In a team project, students are asked to measure acoustics of existing spaces at Concordia, analyze the acoustic quality, and write a report on how to improve them. In the project, students can apply the acoustic theories they learned in actual spaces.

### Building acoustics

The Building Acoustics course (BLDG 474/6721) is a crosslisted course for undergraduate and graduate student who are interested in acoustics for understanding advanced room acoustics. Topics covered in the course include a threedimensional wave equation, sound sources, room acoustics, noise control methods in buildings, acoustic measurement methods such as a room impulse response, transmission loss and sound power measurement. Students are required to practice room acoustic simulation and parameter analysis through case studies and a project. For the project, students are highly encouraged to participate in Acoustical Society of America student design competition with the project outcomes [1].

### Other courses

Noise and Vibration (ENGR 6311) - engineering acoustics course provided by the Department of Mechanical, Industrial and Aerospace Engineering for understanding of wave phenomena in general

Acoustics (ELEC 6361) - electro-acoustics course provided by The Department of Electrical and Computer Engineering mainly for understanding mechanism of loudspeakers, microphones, and communication systems.

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# 3 Acoustic research at Concordia

## 3.1 Laboratory facilities

There are two main acoustic lab facilities in the building engineering program at Concordia. The acoustics and lighting lab is mainly for the laboratory experiments for the course BLDG366. In this class, students attended the lab bi-weekly for acoustic experiments. The laboratory experiments include measurement of the speed of sound, absorption coefficients using a standing wave tube, and reverberation times using an interrupted noise method and an impulse method. The students also learn how to use sound level meters accurately to calculate community noise levels. B&K Impedance tube and Norsonic 140 sound level meters are utilized.

The acoustics research lab is mainly used for research by graduate students. The research lab is equipped with a 2-channel room impulse response measurement system, 3 class 1 sound level meters, a sound intensity probe, 2 tapping machines, an impedance tube, a series of vibration sensors and a reverberation chamber. The volume of the reverberation chamber (Fig. 1) is 15.4 $m^3$ with wall absorption coefficients of 0.06 or less from 250 Hz and upwards. The chamber acts as a source room for random sound absorption coefficient, sound power assessment, and for sound transmission loss measurement. The equipment and lab can be used for acoustic measurements of music venues, transmission loss, sound power, impact isolation, sound source localization, vibration measurement, and sound quality analysis in time and frequency domains. More detailed description can be found in the laboratory and research group homepages [2, 3].

**Figure 1:** Reverberation chamber at Concordia acoustic research laboratory

There are also assorted facilities and resources in the collaboration with the acoustic research group at Concordia. There is a fabrication facility to build acoustic scaled models and material, technical staff with experiences in the acoustic laboratory environment, control systems and signal processing specialist, Building Material Laboratory, and Heating, Ventilation and Air Conditioning (HVAC) laboratory for testing of noise from building mechanical systems.

## 3.2 Research areas

Current research project at Concordia are:

1) perception-based acoustic building design,
2) noise exposure monitoring in acoustically critical spaces.

Potential research interests of our group are:

3) sound quality analysis of HVAC system to develop effective noise control methods,
4) sound source localization and transmission loss using intensity measurement,
5) speech intelligibility and classroom acoustics,
6) concert hall acoustic measurement and analysis.

# 4 Conclusions

The acoustics specialization has been revitalized in the building engineering program at Concordia University to help students to gain knowledge in acoustics as building engineers and pursue further research and professional careers in acoustics. The acoustics courses and research activities support students to engage in acoustic areas.

Building Acoustic Research Group at Concordia University offers prospective graduate and undergraduate students theoretical and practical hands-on academic and research experience in architectural acoustics and noise control methods for design of buildings for optimal acoustics performance.

## Acknowledgments

The authors are grateful to Dr. Ramani Ramakrishnan for his contribution of the acoustic course curriculum. We would also like to thank Dr. Richard Guy for establishing the acoustic program and research laboratories at Concordia University.

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# TEACHING ACOUSTICS TO ARCHITECTS

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## 1 Introduction

Teaching acoustics in most Canadian universities, with one exception, is an exercise in isolation. In many departments across Canada, acoustics is presented to suit the particular student population. Somewhat similar conditions exist in the Department of Architectural Science at Ryerson University. My colleague in the department will discuss his experiences of teaching an undergraduate course to third year architecture students. The current paper will focus on an elective building acoustics course taught at the graduate level. Even though the department is part of the engineering faculty, architects seem to impose a disconnect with engineers. In addition, when architects design spaces the focus is seen to be on possibilities rather than the potential implementation of the design. How to overcome this disconnect is the main obstacle for engineers. Can one still teach a useful and practical acoustics course? The answer to the above vexing problem is the main focus of the current paper.

## 2 Main courses

Currently, two courses are being taught in the Department of Architectural Science at Ryerson University. The undergraduate course ASC 521 is taught to the third year students and is a core course. ASC521 – Light/Sound in Architecture - presents the fundamentals of lighting and acoustic design in buildings. Subjective responses to light and sound are explored. Simple calculations are used to evaluate spatial acoustic and lighting performance. Natural lighting processes and energy management techniques are investigated. Fundamentals of acoustic separation are presented. Students will analyse case studies of a variety of room types, including interior office spaces, public galleries and performance spaces that present opportunities to evaluate sound and light in various applications. Model testing of room acoustic and lighting performances will be introduced.

The sound (acoustic) portion of the course is presented over six (6) 3-hour lectures and is currently being taught by Prof. Umberto Berardi and he will describe his experiences during his presentation.

The elective course (BL8206/ASC905), Advanced Acoustic Design, is taught for graduate students and 4th year undergraduate students. Students from other departments are also allowed to take the course. This course will provide students with opportunities to explore in depth how to provide appropriate acoustical environments within different building types, and their implications on materials and other aspects of performance.

Upon successful completion of this course, the students are expected to:

- Understand the basics of sound in buildings.
- Understand the concept of sound propagation outdoors.
- Understand the concept of acoustical regulations in buildings
- Become familiar with building noise sources and their description.
- Begin to understand the design applications for acoustical spaces.
- Begin to understand the simulation and site measurements of acoustical spaces.

The topics to be covered in the course include:

- Sound Basics- Definitions –decibel (dB) - Sound Descriptors.
- Outdoor Sound Propagation – Sound Perception
- Acoustic Instruments
- Room Acoustics -Absorption – Reverberation – Absorption Coefficient
- Sound Transmission: Transmission Loss
- Building Noise sources and control
- Open Plan Office acoustics
- Basics of Auditorium Acoustics
- Simulation of Performance Space acoustics

The above topics were taught over 13 weeks and the weekly breakdown is listed below.

W#1. Course Management and Introduction: Definitions – decibel (dB) - Sound Descriptors; Sound Propagation – Sound Perception
W#2. Outdoor Propagation; Room Acoustics -Absorption – Reverberation – Absorption Coefficient
W#3. Noise Control Criteria and Regulations
W#4. Instrumentation and Noise Sources
W#5. Walls and Enclosures
W#6. Midterm
W#7. Reading week
W#8. Vibration and Noise Control in Buildings and Building Noise Control – Case Study 1
W#9. HVAC System Control - Example
W#10.Open Plan Office Acoustics
W#11.Auditorium Design guidelines – Example and EASE
W#12.Site Visit
W#13.EASE Simulation – Contd.

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## 3 Discussion

The first thing to be noted is that the title is a misnomer. Most of the students, who sign for the course, have only an architectural degree with scant mathematical background. If the architectural degree is from a foreign country, such as Iran, it would have included some elementary mathematical courses. It can be seen therefore, that the students have difficulty in solving simple problems and considerable tutorial hours have to be expended to assist the students in understanding the materials. Hence, the 'Advanced' in the title of the course is not correct and the course materials have to be simplified as much as possible with the hope that architects can obtain a basic understanding of acoustics and noise control in buildings. It must be reiterated here that the course under discussion is a graduate level course.

One of the aspects that we, as acousticians, have noted over the years, is that architects have ease of using simulation software to model typical building spaces such as auditoria and produce voluminous results such as reverberation time, STI, $C_{80}$, $D_{50}$ etc. However, most of the architects have no clue as to the significance of these terms other than may be that of reverberation time. The above comments becomes self-evident when one reads about major auditoria in the media. The main spokesperson, at least in North America, to discuss and describe the auditorium acoustics is the architect and not the acoustician. So, one of the efforts, undertaken in BL8206, is to describe and define useful acoustic descriptors so that the students (and future architects) would have some semblance of understanding of the building acoustics and noise control.

The question then, "How does one teach a problem solving, technical course to architects?" At the outset, the students were informed that completing the course does not make them into acousticians. However, the course will provide sufficient fundamental information so that as architects they will be able to confer intelligently with acousticians and noise control specialists.

After teaching BL8206 five times over the past ten years, the consensus that can derived is that to teach architects acoustics has been a heart-breaking exercise at times. Since one has to simplify the materials as much as possible, the learning curve in applying the basic principles to complex situations is totally lacking. The following two examples of assignment problems will show the efforts needed to make architects to deal with building acoustical issues.

**Example 1: the following outdoor propagation problem with a single source with octave band SPLs was easily solved by the students which was similar to one of the worked samples during the lecture.**

A manufacturing facility will be testing its engines at a plant location which is 50 m from its property line. The tests will be conducted either at night or day time over a 2-hour period. The steady noise levels at the plant property line are given below. Residential development is located 100 m east of the plant property. Will the plant be allowed to test, without noise mitigation, if it is located, a) in an urban areas; b) in a rural area in Ontario?

However, when a multi-source situation, such as the one below with different operating times, more than 80% of the class was not able to solve the problem.

The plant consists of a bank of cooling towers. Due to the recession, the cooling towers operate only for 50% of the time in any given hour. The steady sound of the cooling towers is dominant in the following two frequencies -250 Hz and 500 Hz. The SPL at a distance of 100 m is 75 dB at 250 Hz and 68 dB at 500 Hz. At night time the plant releases steam through a vent for a period of 2 minutes. The steady SPL at 100 m for the steam vent is 70 dB at 1000 Hz and 65 dB at 2000 Hz. What is the one-hour $L_{eq}$ in dBA a) during the day time and b) at night time?

**Example 2: the following indoor problem with a single source with PWLs in two frequencies was easily solved by the students which was similar to one of the worked samples during the lecture.**

The music room (no windows) of an apartment unit has dimensions 6 m X 5 m X 4 m high. The walls and the ceiling are made with gyproc with absorption coefficient of 0.15 at 250 Hz and 0.10 at 1000 Hz. The floor has thick carpet with absorption coefficient of 0.25 at 250 Hz and 0.65 at 1000 Hz. A small speaker with 0.1 watt sound power at 250 Hz and 1000 Hz was located on the floor at the centre of the 6 m by 4 m wall. Determine the diffused sound level in the room.

However, when a fan with a given sound power was placed inside a closet (the transmission loss properties of the closet were given) at one end of the room, the students had immense difficulty to solve the problem.

It must also be pointed out that only a single acoustics course to discuss building acoustics is being offered and to adequately do justice to the acoustic materials can be seen to be a tall order.

## 4 Conclusion

It is obvious, as it is at departments in other universities in Canada, that the main focus has been to provide acoustical information within a narrow focus. One would hope that the architects understand the acoustical requirements that would make the built environment is adequate from an acoustical comfort perspective. The main requirement, in Canada then, is to offer a full-fledged "Acoustics Program," similar to the ones at John Hopkins and Penn State Universities in the USA where one could obtain a Master's degree in Architectural Acoustics or Building Noise Control.

# SEEING SOUND: A NEW TOOL FOR TEACHING MUSIC PERCEPTION PRINCIPLES

**Maxwell Ng [*1] and Michael Schutz [†1]**
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## 1 Introduction

Interdisciplinary by nature, music perception research holds important lessons for multiple fields of study. Timbre, for example, lends insight into the perceptual and neural mechanisms underlying our experience of both musical and non-musical sounds. Understanding the acoustic consequences and timbral implications of subtle manipulations to bow pressure, embouchure changes, and the types of mallets used are of practical value to performing musicians.

Students from different disciplines approach common issues with different backgrounds and interests. For example, cognitive scientists are primarily interested in how timbre can inform our understanding of the mind, whereas musicians are more interested in how variations in timbre can be shaped to achieve artistic goals. Although these different perspectives are not necessarily incompatible, the ways in which information is most usefully represented and the types of sounds most helpful to analyze/explore differ between these different perspectives.

To help with pedagogical efforts related to music perception, we developed a software tool—MAESTRO—for novel exploration and analysis of musical timbre. Designed to be of use in diverse contexts, it offers the ability to visualize complex instrumental timbres in a variety of formats. Additionally it offers "deconstructions" of musical sounds, giving users the option to both see and hear (a) high quality audio recordings of different instruments, (b) synthesized power spectra generated from the same audio recordings, and (c) tones synthesized from this information tracking changes in each harmonic's time varying amplitude.

## 2 Visualizing musical timbre

### 2.1 Power spectra representations

Most musical sounds are rich in harmonic structure, with overtones varying in strength amongst different instruments. For example, trumpets produce more overtones than clarinets, whose construction deemphasizes even-numbered harmonics [1]. These differences are typically visualized in textbooks using power spectra such as those shown in Fig 1. These representations highlight *one* aspect of acoustic structure that differs between instruments – average harmonic content. MAESTRO's ability to easily compare sonified power spectra to natural sounds allows for clarification of the complex nature of musical timbre.

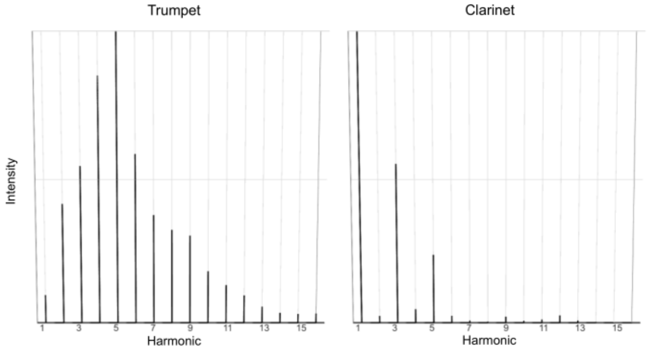

**Figure 1:** Power spectra of a trumpet and clarinet, showing differences in their average harmonic content.

### 2.2 Shortcomings of power spectra

Although power spectra capture certain aspects of the differences between instruments, they do not represent the rich temporal changes in strength of individual harmonics. These changes play an important role in timbre, and attention to these subtle manipulations form a crucial part of musical training (although musicians often talk in more general terms, such as a tone's "warmth" or "harshness", rather than discuss specific overtones). Note that although a waveform representation offers some insight into the temporal structure of sounds, it fails to capture the complex nature of the changes of each independent harmonic as shown in Fig 2.

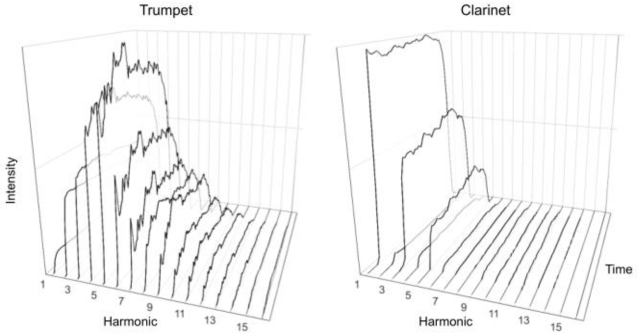

**Figure 2:** Natural musical sounds consist of many harmonics, with the relative strength of each harmonic changing rapidly over the course of the sound's evolution.

## 3 MAESTRO software

### 3.1 Program overview

MAESTRO features multiple concurrent sound representations allowing users to simultaneously explore

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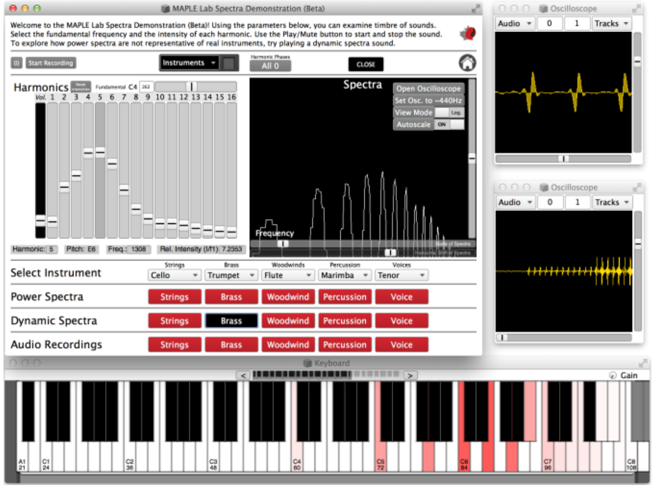
different aspects of a complex sound's acoustic structure. This includes traditional representations, as well as alternative visualizations useful for specific purposes (Fig 3). Additionally, it offers users the opportunity to "edit" power spectra to explore both the auditory and visual effects of varying typical waveforms (e.g. square waves, triangle waves, etc.). This tool is now freely available for non-commercial use at maplelab.net/pedagogy.


Welcome to the MAPLE Lab Spectra Demonstration (Beta)! Using the parameters below, you can examine timbre of sounds. Select the fundamental frequency and the intensity of each harmonic. Use the Play/Mute button to start and stop the sound. To explore how power spectra are not representative of real instruments, try playing a dynamic spectra sound.

Fundamental C4 262

Harmonic: 5
Pitch: E6
Freq.: 1308
Rel. Intensity (I/f1) 7.2353

Select Instrument: Strings Cello, Brass Trumpet, Woodwinds Flute, Percussion Marimba, Voices Tenor

**Figure 3:** MAESTRO allows for simultaneous visualization of sounds in waveform, dynamic spectra, and a new "piano-style spectrum" intuitive for musical students.

## 3.2 Standard sounds

This software allows users to switch between standard acoustic demonstrations of sine, square, triangle, and sawtooth waves. The precise harmonic "recipe" for each tone is revealed in a series of sliders, allowing users to manipulate and explore the effects of changes in each overtone's relative strength. The display also includes amplitude envelope, oscilloscope, and power spectra (using either a log or linear scale for frequency) representations.

In addition to these three standard visualizations, MAESTRO includes two specialized representations useful in further understanding musical timbre. The first maps a note's overtone structure onto a conventional piano keyboard – a representation intuitive for musicians. The second involves continuously-updated sliders that dynamically indicate each harmonic's strength while synthesizing musical sounds. This visually conveys the amount of change in harmonic amplitude found in musical instruments.

## 3.3 Musical instrument sounds

We have included instruments from different instrument categories (brass, woodwind, etc.) based on samples provided by the Iowa Electronic Music Studio library [2].

The software can play recordings of the instruments, as well as two synthesized tones based on the original recording. The first synthesized tone generates a sound with power spectra taken from the real instrument, sonifying traditional descriptions of an instrument's harmonic content. The second version synthesizes the natural temporal variation in amplitude strength, sonifying the dynamic amplitude changes important in an instrument's harmonic content. This multi-faceted approach using different perspectives has been useful in teaching interdisciplinary classes consisting of students from a variety of backgrounds.

## 4 Conclusions

This tool provides a useful path to compelling auditory demonstrations in classroom settings. Developed primarily for teaching music and psychology students, it could be useful in courses focused on acoustics, sound synthesis, and other disciplines. Additionally, it holds the potential for pedagogical use in applied musical settings by providing new insight into nuanced differences in acoustic structure.

This software highlights the importance of dynamically changing amplitude information in our perception of musical sounds. Our interest stems in part from growing awareness of the under-studied role of amplitude envelope in auditory perception. Although real world sounds generally exhibit dynamic changes, perception research overwhelmingly focuses on amplitude invariant "flat" tones [3], which risks leading to conclusions failing to generalize to real world sounds [4]—such as those used in music.

## Acknowledgments

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# ABSTRACTS FOR PRESENTATIONS WITHOUT PROCEEDINGS PAPER
# RÉSUMÉS DES COMMUNICATIONS SANS ARTICLE

## Use Of Acoustical Standards In The Audiology Classroom

*Christian Giguère*

Audiologists are primary providers of hearing healthcare. As part of their scope of practice, they perform detailed evaluations of the auditory function, prescribe hearing aids and other assistive listening devices, offer counseling and aural rehabilitation services, and participate in hearing loss prevention activities. In Canada, Audiology is taught at the Master's Degree level, typically in an intensive 2-year program. Applicants are from a wide variety of disciplines (e.g. psychology, linguistics, education, health sciences) where acoustic measurements and use of electroacoustic instruments (e.g. audiometers, hearing aid analyzers) are not part of the curriculum. From a pedagogical perspective, acoustical standards provide an important vehicle for introducing proper terminology and keys concepts in acoustics and instrumentation. Through laboratory assignments and other learning activities, hands-on experience can be gained on the operation, calibration and tolerance limits of clinical instruments. From a professional perspective, self-regulated health colleges such as the College of Audiologists and Speech-Language Pathologists of Ontario issue Practice Standards and Guidelines (PSGs) and/or position statements on equipment use and servicing requirements for their Members that refer to specific acoustical standards, especially from the ANSI S3 series on Bioacoustics. This paper will focus on the use of audiometry standards (e.g. ANSI S3.1, ANSI S3.6) and hearing aid characteristics (e.g. ANSI S3.22) in the Audiology classroom as well as other CSA and ISO standards relevant to the profession.

## Enseignement De L'acoustique En Conception Intégrée

*Jean-Philippe Migneron, André Potvin, Claude MH Demers, Louis Gosselin*

Depuis maintenant quelques années, l'atelier d'ambiances physiques présenté dans le cadre du programme de maîtrise professionnelle a été renouvelé afin d'y ajouter une collaboration multidisciplinaire. En effet, les étudiants de 4e année en architecture choisissant cette option durant un semestre doivent maintenant faire équipe avec des étudiants en génie mécanique, génie civil, de même qu'en génie des matériaux en bois. Bien que le travail en groupe de 4 à 8 personnes durant les différentes phases de conception d'un projet puisse représenter de nombreux défis, cette nouvelle approche a néanmoins l'avantage de sensibiliser chacun aux processus de conception intégrée qui deviendra probablement la norme durant leurs futures carrières respectives. Outre l'apprentissage de certains outils de conception des bâtiments avec des maquettes numériques (BIM), les itérations des propositions permettent d'optimiser toute une panoplie de performances, notamment en termes de consommation énergétique. Selon le contexte, l'acoustique architecturale est examinée à l'échelle urbaine pour gérer l'exposition du projet au bruit communautaire, jusqu'à l'analyse détaillée des compositions des parois. En attendant que les logiciels de modélisation des données du bâtiment incorporent les performances acoustiques à la liste des fonctions disponibles, il est espéré que tous ces professionnels en devenir pourront conserver certains réflexes quand il leur faudra tenir compte des problèmes de bruit lors de projets ultérieurs.

## Aeroacoustics And Aircraft Noise

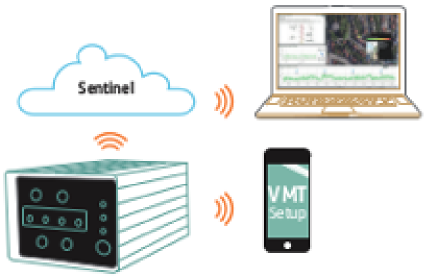
*Joana Rocha*

Noise generated by aircraft is a common complain nowadays, specially for communities near airports. The reduction of noise from aerodynamic origin is one of today major industrial challenge, specially in the field of aviation, even more considering the gradually more stringent noise standard from ICAO (International Civil Aviation Organization). It is therefore desirable to accurately predict the noise generated by turbulent flows, so the noise reduction can effectively be addressed. Aeroacoustics is the study of noise generated by turbulent fluid motion, and by aerodynamic forces interacting with solid surfaces. Aeroacoustic involves coupled aerodynamic and acoustics phenomena. Because of the multi-disciplinary nature of Aeroacoustics and the diversity of the potential applications, Aeroacoustics courses are typically complex and taught at the graduate level and/or at the last year of graduation, requiring the student to be familiar with mathematics, physics and computational techniques. This paper will outline a number of important topics to consider when studying aeroacoustics and aircraft noise, from fundamental concepts to the more advanced and complex topics. Applications to engineering and industry problems are also presented. Both subsonic and supersonic flows are discussed, with emphasis given to turbulent flow induced noise in aircraft.

## Teaching Acoustics To Psychology And Neuroscience Students

*Frank A. Russo*

In this talk I will present my experience with teaching acoustics to psychology and neuroscience students. This will include consideration of work with undergraduates in a psychology of music class as well as graduate studies embarking on research in the cognitive neurosciences of music. In general, these students do not possess a background in physics or signal processing. Many phenomena in acoustics need to be considered from a conceptual perspective. Phenomena that we typically address include harmonic structure and its relation to octave equivalence; sound propagation and its relation to auditory scene analysis; and spectral and temporal features that may be used to predict variability in behavioral responses to music (e.g., dancing). In some cases, students are inspired by this conceptual understanding and choose to dive deeper, developing their own computational implementations of features. In other cases, students prefer to rely on toolboxes that have implementations of acoustic features that have been programmed by others. A perennial challenge is dealing with varying levels of rudimentary knowledge within the same group of students. Regardless, my experience suggests that all students benefit from a multidisciplinary approach that considers the same concept from multiple perspectives, and from ample use of audio demonstrations.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# ENVIRONMENTAL NOISE - BRUIT ENVIRONNEMENTAL

# NOISE CHARACTERIZATION AND REDUCTION TECHNIQUES OF MULTIPLE AXIAL FANS UNIT

**Nadim Arafa** [*1] **and Atef Mohany** [†1]
[1]University of Ontario Institute of Technology, Oshawa, Ontario, Canada.

## 1 Introduction

Digital display units usually utilize axial fans to force cooling air into enclosed spaces to regulate temperature whenever needed. The fluid-sound interaction between the air passing through the fan and the casing can lead to noise radiation that may be very unpleasant. This noise is usually attributed to the interaction of the rotating blades with the fan casing as the dominant frequency in the noise spectra usually matches the blade passing frequency (BPF). The blade passing frequency noise, being tonal in nature, causes greater discomfort compared to normal broadband noises; therefore it became a major design aspect in the construction of axial fans. The noise can further be unpleasant and destructively loud if the frequency of the passing blades is coupled with an acoustic mode of the enclosure [1, 2].

Noise control of axial fans is divided into two approaches, active or passive. The active noise reduction technique depends on the concept of measuring the noise under consideration and adopt a corrective technique to provide destructive interference between the source and the emitted anti-wave. In the passive technique, geometrical modifications are adopted to dissipate or prevent the source from building up loud noise [3]. The current study focuses on the use of passive noise reduction techniques such as downstream silencers in the attenuation of axial fans noise. Different silencer designs are investigated such as, L-shape maze, annular, and absorptive/reflective silencers in order to reach an optimum passive noise control technique.

## 2 Experimental setup

The noise characterization measurements took place in a hemi-anechoic room that has an overall background noise of 29 dBA. The tested fan unit comprises of three axial fans controlled by a speed control module. The fans are tested at normal operating condition, i.e. 50% of the full rotational speed, and at the maximum operating condition. The acoustic mapping measurements were performed using free-field microphones fixed at different locations above the fan unit, which was extracted from an outdoor display unit, as shown in Figure 1. The measurements are performed at discrete points following a measurements grid in order to locate the noise source and obtain an average overall sound pressure level. Several silencers are constructed following the common practices in the industry. The first tested silencer comprises an L-shaped maze in order to allow flow through the maze but break up the noise line of sight, as shown in Figure 2a. The second silencer consist of two concentric hollow cylinders with acoustic insulation filling the empty annulus, as shown in Figure 2b. The third silencer is much more compact than the first two silencers and it is designed to allow the flow out from the fans through a perforated cylinder fitted with reflective plates to distort the noise.

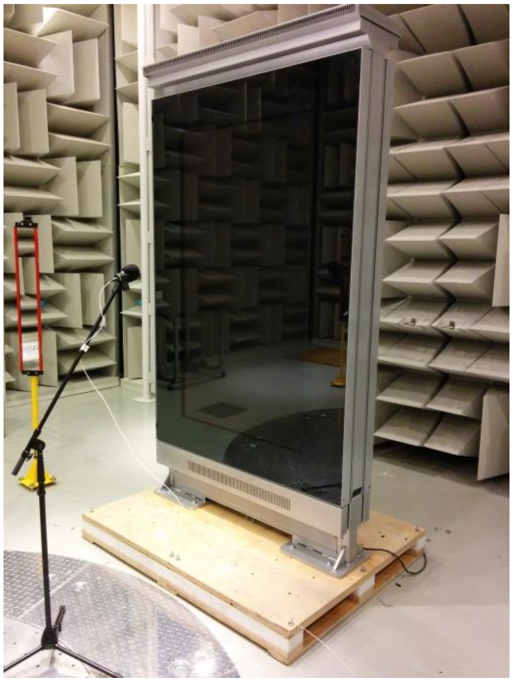

**Figure 1:** Picture of the outdoor display unit comprising the multiple axial fans unit under investigation.

## 3 Results

Figure 3 shows a spectral analysis sample of the noise signal measured above the multiple fans unit at normal operating conditions. The figure shows that, in addition to the turbulent flow noise at the low frequency range, there is a significant contribution by a tonal noise that occurs at 445 Hz. Measurements of the rotation speed at this condition show that the blades are rotating at 5370 rpm, which corresponds to a blade passing frequency of 447.5 Hz, based on the equation:

$$f = \frac{\omega N}{60} \quad (1)$$

Where ω is the rotation speed in rpm and $N$ is the number of blades (5 blades in this case). The measurements show a maximum noise peak of 70.9 dB at the blade passing frequency. Similar behaviour is obtained at the maximum

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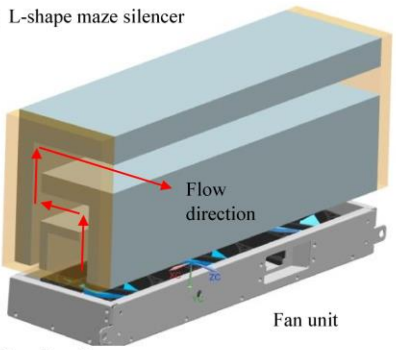
operating conditions where the noise level is elevated to 89.7 dB at a frequency of 943 Hz. The rotational speed at the maximum operating conditions is 11370 rpm, which is almost twice that of the normal operating conditions. Yet, it is observed that the sound pressure level is increased by 20 dB approximately, which means that the resulting acoustic pressure has increased by an almost one order of magnitude.

(a) L-shape maze silencer



(b) Annular silencer

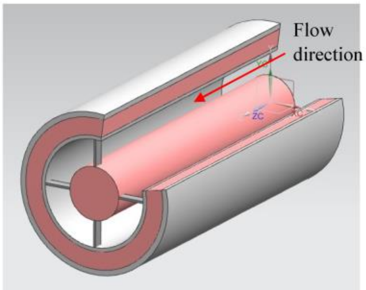


**Figure 2:** Drawings of the different silencers used in attenuating axial fans noise.

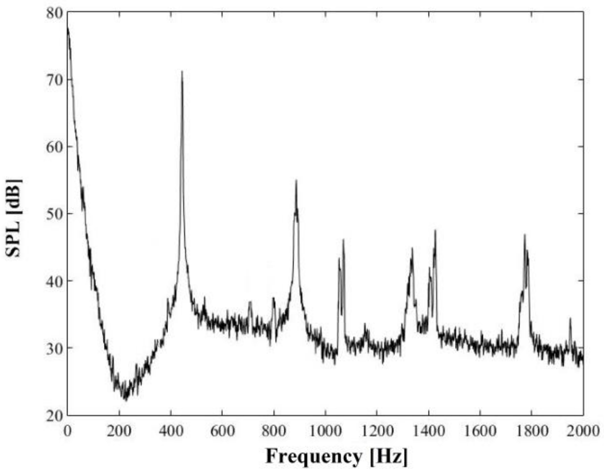
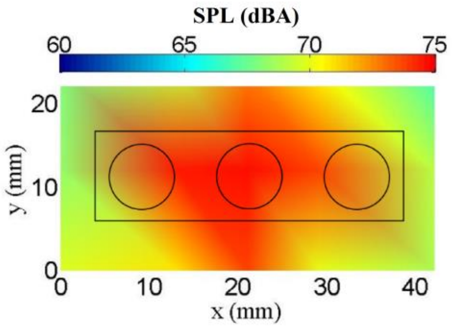
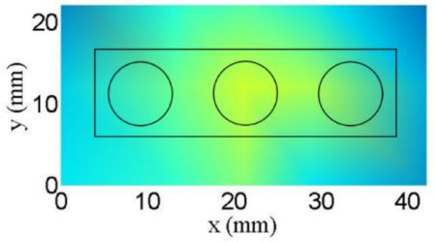


**Figure 3:** Sample of spectral analysis of the noise signal above the multiple fans unit at normal operating conditions.

The overall sound pressure level is mapped above the multiple fans unit, as shown in Figure 4a. The averaged sound pressure in normal operation is 70.7 dBA and goes up to 90.1 dBA in the maximum operation. The use of the different silencers showed good results in attenuating the noise from the fans unit, as shown in Figure 4b. The compact reflective/absorptive silencer that was specifically designed for this multiple fans unit showed the most promising results in attenuating the noise among the other silencers, as summarized in Table 1.



**(A) Base Case – Normal Operation**



**(B) L-Shape silencer – Normal Operation**

**Figure 4:** Contour plot of the overall sound pressure levels above the fans unit at the normal operating conditions.

**Table 1:** Summary of the attenuation obtained by each noise reduction technique (dBA).

| | Normal operation | Max. operation |
|---|---|---|
| L-shape silencer | 5.3 | 4.4 |
| Annular silencer | 6.1 | 6.9 |
| Reflective silencer | 6.3 | 9.5 |

## 4 Conclusion

An experimental characterization of the noise generation from a multiple axial fans unit is presented in this work and several noise reduction techniques are investigated. Comparison of different silencers that were designed specifically for noise reduction from axial fans show that the best approach is to incorporate reflective and absorptive aspects into the construction of a silencer. An innovative silencer design is proposed and shows better results than conventional L-shape maze or annular silencers.

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# DISCUSSION ON NOISE AND ITS IMPACT ON BIRDS

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## 1 Introduction

Birds usually perceive humans as potential predators and may leave their nests in response to being approached, or abort nesting because of stressful situations. There is a negative relationship between the human disturbance (both type and magnitude) experienced by a nesting bird or colony and its breeding success. Human generated noise, from construction, traffic or industry, is one type disturbance that needs to be addressed and regulated to ensure breeding success of nesting birds.

## 2 Environment Canada guidance

Environment and Climate Change Canada (ECCC) has a noise criteria related to birds [1]. This is specific to land birds; as a separate guideline [2] for noise impact was developed for sea and water birds. ECCC has identified the following noise criteria for assessing impact to land birds: disturbance to birds associated with noise when noise is either 10dB above ambient OR greater than 50dB. ECCC caveats this as advice only, is general information and is not official advice concerning legality of any specific activity. However, for the purpose of environmental assessment for noise impact related to birds, this has been adopted for review and approval purposes such that noise experts may be required to monitor and predict noise levels, and wildlife experts to provide assessment of ambient and predicted noise levels with respect to these criteria.

## 3 ECCC criteria review

The ECCC based the development of the 50 dB / 10 dB above ambient criteria for noise impact based on references [3 - 6], and [10]. Highlights of these references as related to the ECCC criteria include : impact for traffic noise based on the Moerkerken & Middendorp [7] traffic noise model, using an LAeq24 noise level [3] ; reference is at 0.5m above the ground surface [3] ; noise level investigated ranged from 59 +/- 6 dBA to 38 +/- 5 dBA [3] ; threshold value (note: Threshold is taken at a noise level where 1% of the bird population leaves an area) of 47 dBA for all species combined and 42 dBA for the black-tailed godwit [3] ; for songbird breeding and migration habitat, from April 1st through June 30th, reduce noise levels to 49 dBA or less within breeding habitat of songbirds to minimize the effects of continuous noise on species that rely on aural cues for successful breeding [4] ; to avoid disrupting auditory displays and nesting at occupied leks (note: a lek is an aggregation of male animals gathered to engage in competitive displays, lekking, that may entice visiting females which are surveying prospective partners for copulation. Leks are commonly formed before or during the breeding season), from March 15 through May 15, continuous or frequently intermittent noise should not exceed 10 dBA above the natural, ambient noise measured at the perimeter of any occupied sage-grouse lek [4, 5] ; for nesting & early brood-rearing habitats, from March 15 through June 30, sources of continuous or frequent intermittent noise should not exceed 10 dBA above natural ambient or background noises measured in any suitable nesting or broodrearing habitat within 2 miles of an occupied lek, or within identified nesting and brood-rearing habitats outside the 2 mile perimeter [4],[5].

## 4 Supplemental literature review

Supplemental reference [8] identified noise disturbance of meadow birds from railway noise, with the following items of note:

- Standard Dutch noise calculation scheme (not referenced) used for prediction of noise, using the LAeq24 assessment at 1m above ground
- Other noise metrics were reviewed (peak noise level) but correlation to disturbance did not improve
- Noted that threshold values varied little between species, though the uncertainty could be large (30-57 dBA for black-tailed godwit)
- Noted that for black-tailed godwit, area loss of between 16-23% of total area within 45 dBA of rail noise contour
- Threshold noise levels : Garganey 49 dBA ; Black-tailed godwit 45 dBA; Skylark 42 dBA; All Meadow Birds 44 dBA; All waders 45 dBA

Caltrans [9] developed interim compliance guidelines (presented in Figure 1 and Table 1). They have defined four Zones of Concern to address potential affects including behavioural and/or physiological effects, damage to hearing from acoustic overexposure and masking communication signals and other biologically relevant sounds:

a) Zone 1: Bird is close to noise source such as traffic and construction noise
b) Zone 2: Bird is at greater distance from the roadway, where hearing loss and permeant threshold shift are unlikely to occur
c) Zone 3: Bird is at even greater distance, where spectrum level is still at or above the natural ambient noise level, masking of communication signals from this added noise may occur.

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d) Zone 4: Noise falls below ambient noise level in critical frequencies of communication (2-8kHz), masking is no longer an issue. However, faintly heard sounds such as low rumble of trucks or alarm, may lead to a chronic state of increased arousal, and thus, lead to other behavior and/or psychological effects

e) Beyond Zone 4: Energy in traffic and construction noise at all frequencies is completely inaudible (falls below the level of the ambient noise). Birds cannot hear this noise and thus, the noise has no effects of any kind on the bird.

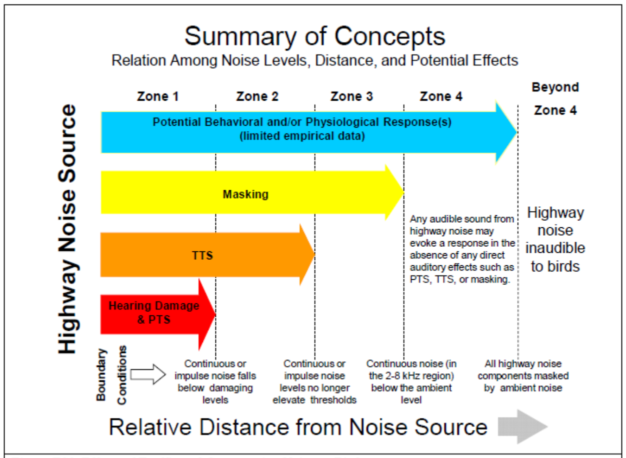

**Figure ES2. Effects of Traffic and Construction Noise on Birds**

Categories of traffic and construction noise effects on birds with distance from the source. Zone 1 is closest to the source while Zone 4 is farthest away. Sound level decreases farther from the source. See text for discussion.

**Figure 1:** Caltrans zones of concern for bird noise impact [9]

**Table 1:** Caltrans interim noise guidelines for potential effects on birds [9]

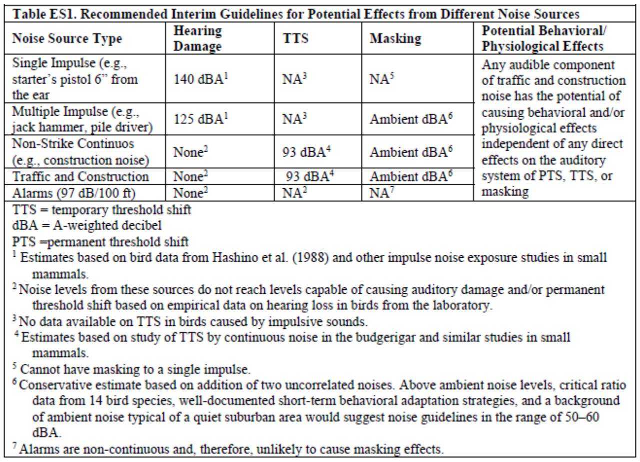

**Table ES1. Recommended Interim Guidelines for Potential Effects from Different Noise Sources**

| Noise Source Type | Hearing Damage | TTS | Masking | Potential Behavioral/ Physiological Effects |
|---|---|---|---|---|
| Single Impulse (e.g., starter's pistol 6" from the ear | 140 dBA[1] | NA[3] | NA[5] | Any audible component of traffic and construction noise has the potential of causing behavioral and/or physiological effects independent of any direct effects on the auditory system of PTS, TTS, or masking |
| Multiple Impulse (e.g., jack hammer, pile driver) | 125 dBA[1] | NA[3] | Ambient dBA[6] | |
| Non-Strike Continuos (e.g., construction noise) | None[2] | 93 dBA[4] | Ambient dBA[6] | |
| Traffic and Construction | None[2] | 93 dBA[4] | Ambient dBA[6] | |
| Alarms (97 dB/100 ft) | None[2] | NA[2] | NA[7] | |

TTS = temporary threshold shift
dBA = A-weighted decibel
PTS =permanent threshold shift

[1] Estimates based on bird data from Hashino et al. (1988) and other impulse noise exposure studies in small mammals.

[2] Noise levels from these sources do not reach levels capable of causing auditory damage and/or permanent threshold shift based on empirical data on hearing loss in birds from the laboratory.

[3] No data available on TTS in birds caused by impulsive sounds.

[4] Estimates based on study of TTS by continuous noise in the budgerigar and similar studies in small mammals.

[5] Cannot have masking to a single impulse.

[6] Conservative estimate based on addition of two uncorrelated noises. Above ambient noise levels, critical ratio data from 14 bird species, well-documented short-term behavioral adaptation strategies, and a background of ambient noise typical of a quiet suburban area would suggest noise guidelines in the range of 50–60 dBA.

[7] Alarms are non-continuous and, therefore, unlikely to cause masking effects.

## 5 Conclusion

For compliance with the ECCC guideline of 50 dB and 10dB above ambient for nesting birds: 1) a 50 dBA, LA24hreq criteria should be adopted, compliant with previous research methodology; 2) calculation of a 10 dB ambient increase should be considered on the basis of a LA24eq criteria, compliant with previous research methodology. Further, threshold ranges can be lower than 50 dBA for some bird species, and these threshold ranges, based on research from the black-tailed godwit, could have a wide range of impact (30 – 57 dBA). Because of these uncertainties, the 50 dBA criteria should be considered a potential threshold limit, to trigger investigation into the specific species impact and field investigation of impact on the local bird population. Also, the time of year (March 15 through June 30), should be considered with respect to the noise impact period. Further consideration should include noise assessment with respect to avian loudness contours.

For the purpose of environmental impact assessment of noise on birds, and further to the ECCC impact, adoption of the CALTRANS technical guidance document can be considered. This includes assessment of bird impact based on Zones (1-4) with respect to Classes of Potential Effects: Behavioural and/or physiological effects; Damage to hearing from acoustic overexposure; Masking of communication signals and other biologically relevant sounds.

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# AN ANALYSIS OF TWO CITIES AND A STATE WHERE CONSTRUCTION NOISE AND VIBRATION ARE UNIQUELY REGULATED

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## 1 Introduction

In Canada and the United States, there are three places where construction noise and/or vibration are uniquely regulated by government authorities. These include the City of Toronto (Ontario), the City of New York, and the State of California. The regulations require studies prior to construction activity and/or monitoring of noise and vibration during construction. The underlying objective of these regulations represents either a commitment to avoidance of damage to structures that are in proximity to a construction site, or the reduced probability of public annoyance.

To be clear, this isn't just about the nuisance factor of industrial noise/ vibration. Current regulations do not consider the potential for significant and adverse effects on the operations of healthcare facilities and research laboratories, where sensitive instrumentation and equipment may be in use. In these cases, the requirements for control of noise and/or vibration can often be much more restrictive.

## 2 Overview of regulations

### City of Toronto

#### Toronto municipal code, chapter 363, building construction and demolition, by-law 514–2008, construction vibrations

Uniquely among comparable jurisdictions in Canada and the USA, Toronto has had a vibration bylaw since May 27, 2008. There are no stated restrictions on the times of day when construction vibration may be created. There are no descriptions within the bylaw of exemptions for different types of construction activity and/or allowable vibration.

The construction equipment is assessed for vibration concerns within a "zone of influence" (ZOI) which is defined by a radius away from construction activity where the vibration amplitudes are excessive. Within this ZOI, the bylaw defines "prohibited construction vibrations" to be those that exceed a stipulated peak particle velocity of 8 mm/s below a frequency of 4 Hz, 15 mm/s from 4 to 10 Hz, and 25 mm/s for a frequency range above 10 Hz. An applicant for a permit must submit a vibration control form that relies upon a preliminary study, prepared by a professional engineer. The vibration control form identifies the places where the ZOI extends beyond the boundaries of the construction site and identifies any buildings that are designated under the Ontario Heritage Act. Where necessary, mitigation is recommended.

The bylaw requires a monitoring program in order to document compliance. Both the mitigation and the monitoring program must be described in the documentation submitted for permitting of the construction work. Complaints must be investigated by a professional engineer.

### City of New York

#### Local laws of the city of New York for the year 2005, No.113, noise control code and construction rule of January 18, 2007

The City of New York has enacted a "local law" whose objective is citywide mitigation of construction noise [2]. To comply, every construction site with activity must submit a Construction Noise Mitigation Plan (CNMP) to the Department of Environmental Protection (DEP). The permit holder for construction work is expected to offer a formal noise mitigation training program to benefit supervisors.

The contents of the CNMP include a self-certification that the construction equipment have noise emissions that achieve normal manufacturer's operating specifications at peak loading. The DEP itself makes use of a stipulated software for assessing noise complaints, the Federal Highway Administration (FHWA) Roadway Construction Noise Model (RCNM), as published January 2006. The RCNM and the contents of the Construction Rule make use of a defined set of noise emissions for a wide range of construction equipment. Within the Construction Rule, authorized work hours range from 7 AM to 6 PM on weekdays, with the possibility for securing after hours times through a permit. The DEP has the power to require additional noise mitigation. The contractor is expected to coordinate hours of work to minimize the expected noise impact to schools, hospitals, places of worship and homes for the aging.

The Construction Rule provides a set of stipulations for noise mitigation in conjunction with the presence of any of five defined classes of construction equipment:

- Impact Equipment: Pile Drivers, Jackhammers, Hoe Rams, Blasting.
- Earth Moving Devices: Vacuum Excavators.
- Construction Trucks: Dump Trucks.
- Stationary Devices: Cranes, Auger Drills, Street Plates, Backup Alarms.
- Manual Devices: Concrete Saws.

For each of these classes of construction equipment, the stipulations include: source controls, such as quieter models, mufflers and/or silencers; noise pathway controls, such as noise barriers, enclosures and/or curtains. Noise barriers,

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both permanent and temporary, must be built to achieve a sound transmission class (STC) rating of 30 or greater with a general expectation that noise levels at sensitive receptors will be reduced by 5 dB or more. The Construction Rule even recommends specific makes and models of construction equipment as the preferred options.

**State of California**

**California environmental quality act (CEQA) 1970**

The CEQA [3] is a legislation that defines "Environment" [as meaning] the physical conditions that exist within the area which will be affected by a proposed project, including land, air, water, minerals, flora, fauna, noise, or objects of historic or aesthetic significance [CEQA 21060.5]. It defines "noise" as a part of the environment. Both the long-term operations of projects and short-term construction activity are subjected to study before a project begins through the preparation of a comprehensive environmental impact report (EIR) that is subject to review by a lead agency, such as a state, county, or city agency; along with opportunity for public input.

A "project" within an EIR is defined by a range of feasible alternatives, each potentially requiring different mitigation. One of these is designated as the preferred alternative. In the case of construction noise and vibration, the objectives of an EIR are to document whether or not there is a "significant effect on the environment" when considering a quantitative "threshold of significance". Where there is a significant effect (i.e., "impact"), mitigation will be developed to prevent or minimize damage to the environment. The resulting project is then defined to include the entirety of the required mitigation and a "mitigation monitoring plan" will also be implemented during construction.

The following excerpt from a CEQA checklist is typically applied when assessing whether or not project noise or vibration would result in either "no impact", "less than significant impact", "less than significant impact with mitigation", or a "potentially significant impact" by asking whether or not the project would result in:

- Exposure of persons to or generation of noise levels in excess of standards established in the local general plan or noise ordinance, or applicable standards of other agencies?
- Exposure of persons to or generation of excessive ground borne vibration or ground borne noise levels?
- A substantial temporary or periodic increase in ambient noise levels in the project vicinity, above levels existing without the project?

From the aforementioned, although CEQA is very comprehensive in terms of required analysis of construction noise and vibration prior to short-term construction and long-term operation, the lead agency would need to stipulate any and all thresholds of significance that are acceptable for determinations of impact due to construction activity. Similarly, the development of mitigation by the project sponsor will rely upon the defined thresholds of impact. The extent to which the definition of a threshold of impact can rely upon a noise ordinance would vary with jurisdiction.

## 3 Lessons learned

To summarize, the following can be learned by considering the regulations in places for these two cities and a state:

- Construction Vibration is subject to quantitative limits in the City of Toronto, whereas, construction noise is addressed within a bylaw in less strict terms;
- Construction Noise is subject to very extensive mitigation requirements in the City of New York, but there is no comparable regulation of construction vibration;
- Construction Noise and Vibration, both, are subject to environmental study prior to project approval and permitting in the State of California. Quantitative thresholds of significance for construction noise and vibration are developed on a case-by-case basis by the project sponsor, with the lead CEQA agency having to agree to them; and
- Documentation of the possible environmental effects prior to project construction is as follows for these three places:
    - City of Toronto: preliminary study and vibration control form.
    - City of New York: Construction Noise Mitigation Plan.
    - State of California: Environmental Impact Report.

## 4 Conclusion

In the three cases cited in this article, the expectation is for construction contractors to comply with the regulations and/or bylaws and produce documentation both before and during periods of work at a site. (The time to start complying with regulations is long before the actual building process begins.) The engineering expertise required to generate such documentation is generally outside the scope of a construction contractor – to deliver quality projects, on time and on budget – which is why outside assistance is generally required and highly recommended.

Distilled to its simplest message, our best solutions going forward include better equipment, better processes and better barriers for noise and vibration. Specialists maintain an inventory of state-of-the-art instrumentation that is used to measure construction noise and vibration, as well as experienced, professional staff to help clients achieve regulatory compliance. Such instrumentation for monitoring may be prudent in situations not explicitly considered by regulations, including, for example, healthcare facilities, research laboratories and microelectronics manufacturing.

## References

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[3] https://oag.ca.gov/environment/ceqa

# QUANTITATIVE DIFFERENCES IN HIGHWAY NOISE LEVELS DUE TO PAVEMENT TYPE: IMPACT ON MODELLING FUTURE NOISE EMISSIONS

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## 1 Introduction

This article provides an overview of three highway-noise models in use in Canada or the USA, the capacity of these models to accurately represent noise emissions from different types of pavements, and the constraints that are imposed in some jurisdictions that compromise the accuracy of modeling, particularly with forecasting of future noise levels. Ideally, calculated noise levels will agree with measured levels of highway noise. In Canada and the United States, there are three commonly used computer models used to predict noise levels due to highways: STAMSON 5.0, an older model developed in Ontario, Canada that follows a defined model [1]; STAMINA 2.0, an older model developed in the USA [2]; and the Traffic Noise Model (TNM) [3, 4] that has superseded STAMINA 2.0 and was also from the USA.

STAMSON 5.0 and the TNM allow for some user-defined control over the type of pavement that is assumed for modeling purposes; whereas STAMINA 2.0 does not unless an alternative version of the software is used that incorporates alternative noise-emission properties (e.g., Sound2000 as developed for the State of California).

The general classifications of pavement for this article include three types: Portland cement concrete (PCC), dense-grade asphalt concrete (DGAC) and open-grade asphalt concrete (OGAC). A PCC pavement is typically tined, or grooved, either longitudinally in the direction of travel or transversely. An OGAC pavement has increased porosity to airflow relative to a DGAC pavement. American Federal regulations stipulate that the "average" pavement is used which is calculated by averaging the noise emissions of measurement results for DGAC and PCC pavement types.

## 2 Ontario, Canada highway noise emissions / STAMSON 5.0

Figure 1 shows a comparison of the Reference Energy Mean Emission Levels (REMELs) for three vehicle types as used in STAMSON: automobiles, medium trucks and heavy trucks. The horizontal axis is the speed, in miles per hour (mph), and the vertical axis is the noise-emission level in A-weighted decibels. The noise-emission levels shown are typically at a reference distance of 15 m (50 ft) from the center of the lane traveled by a passing vehicle. These calculations assume typical asphalt or concrete (i.e., DGAC pavement type). The STAMSON model allows for adjustments of the calculated sound level for OGAC (-2.5 dBA), DGAC (0 dBA) and PCC (+7 dBA).

## 3 USA highway noise emissions: reference energy mean emission levels (REMELs)

STAMINA makes use of REMELs for vehicle noise that describe noise emissions from vehicles over a range of speeds. The coefficients for the National REMELS for the three STAMINA vehicle types are based on data collected in 1975 in the states of North Carolina, Florida, Washington, and Colorado. These STAMINA coefficients were never revised by the USA Federal Highway Administration (FHWA). Concerns arose that this first-generation of National REMELs was leading to noise-level predictions that were too high. In the 1980s, at least two state DOTs (California [5] and Georgia [6]) derived their own REMELs.

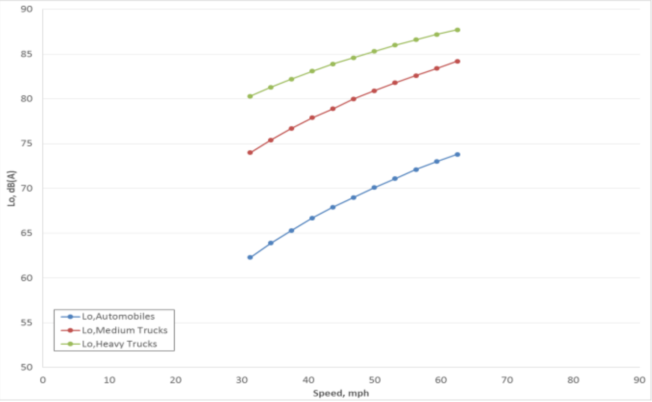

**Figure 1:** REMELs for automobiles, medium trucks and heavy trucks from STAMSON 5.0 assuming DGAC pavement type.

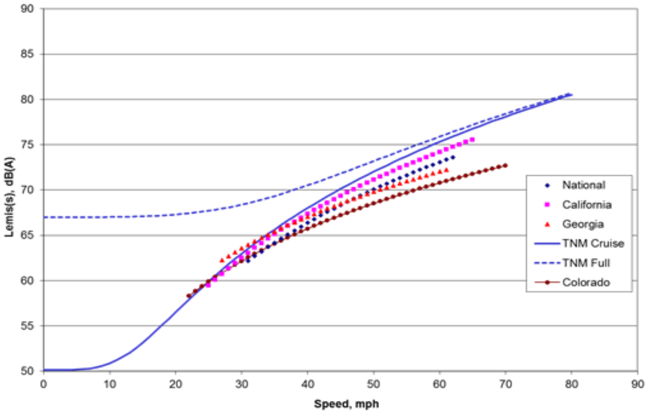

**Figure 2:** REMELs for automobiles from STAMINA 2.0/TNM.

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New National REMELs for the TNM were developed [7]. From measurements in California, Florida, Massachusetts and Tennessee, parameters were developed to describe speed-dependent changes due to vehicle type (A), vehicle and pavement type (B), and vehicle and throttle condition (C). Regressions were performed against the L(A),fmax as a function of speed to derive the coefficients A, B, and C for the cruise condition of a passing vehicle. Under full-throttle conditions, the measurements were repeated and values of coefficient C was derived in accordance with techniques for measuring noise from vehicles under acceleration. Due to the influence of parameter C at lower speeds, the values of A and B derived for the TNM will be altered so they are not, strictly speaking, directly comparable to the values derived for use with STAMINA which are limited to an A and B value of the form B + A log10(speed).

The REMELs for National, California, Georgia, and TNM are presented in Figure 2 for automobiles, Figure 3 for medium trucks, and Figure 4 for heavy trucks. The horizontal axis is the speed, in mph, and the vertical axis is the noise-emission level in A-weighted decibels. TNM curves were calculated from the coefficients for “Average” pavement.

## 4 Discussion and summary

For STAMSON there are three distinct classifications of pavement type. For each of these pavement types, the adjustments shown for noise emissions are presumably some sort of an average that corresponds to each distinct type. However, the supporting documents for STAMSON do not provide literature references to substantiate the recommended pavement-type adjustments. For STAMINA, the software employs a National “Average” that does not differentiate between the noise emissions for each type of pavement.

For the TNM, the “Average” in this context can refer to both the noise emissions that are claimed for each distinct type of pavement along with an “Average” that has been determined in some unspecified manner from the reported noise emissions of PCC and DGAC. However, the methodologies used for averaging are not entirely clear.

The regression coefficient B differs for both the DGAC and PCC pavement types and for the resulting average of those two pavement types. Inexplicably an examination of these regression coefficients indicates the following when it comes to the average pavement type: for automobiles, the assumption is 84% DGAC and 16% PCC; for medium trucks, the assumption is 75% DGAC and 25% PCC; and for heavy trucks, the assumption is 59% DGAC and 41% PCC.

## 5 Conclusion

For assessments of environmental impacts of highway noise, the forecast of future noise levels will ideally agree with post-construction measurements. Many factors come into play including the type of pavement. When predictions are inaccurate, impacts may incorrectly be forecast, or not, depending on the adjustments to parameters involved as part of the calculations. As such, this paper has provided information that is relevant to those with an interest in accurate forecasts of future noise levels. The assumption of either an incorrect pavement type or an “average” noise emission of some kind when it comes to noise emissions from pavements does not support this reasonable objective. The varying proportions of DGAC and PCC used to calculate the TNM REMELs average deserve more investigation.

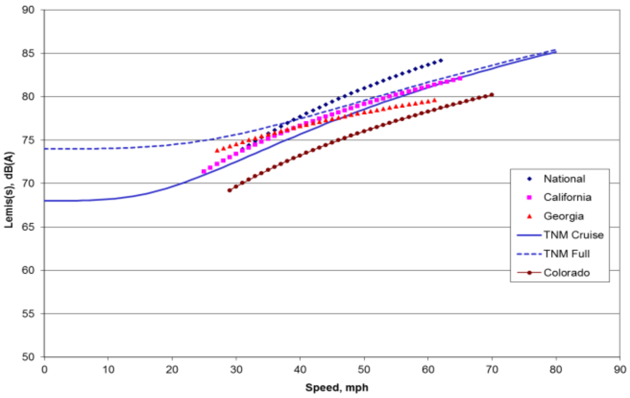

**Figure 3:** REMELs for Medium Trucks from STAMINA 2.0/TNM

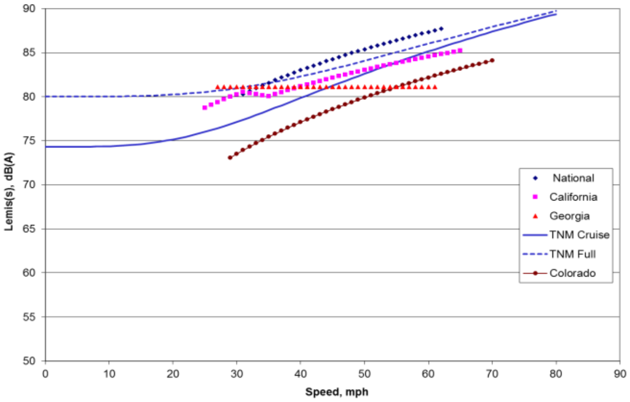

**Figure 4:** REMELs for heavy trucks from STAMINA 2.0/TNM

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# Quality Assured Software Implementation Of ISO 9613-2 According To ISO/TR 71534-3

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## 1 Introduction

The ISO 9613-2 standard is a well-known method for the calculation of industrial environmental noise. The standard was published in 1996 and since then has been implemented in numerous commercial software applications. The standard however, does not contain quality requirements for applications, such as test cases and recommendations for implementation. Therefore, the calculated results of different software implementations for the exact same situation cannot be expected to be the same. When comparing different software implementations of ISO 9613-2 the results can differ up to 5dB for simple situations and up to 10dB for complex situations. This makes the result of noise prediction even more uncertain. Not because of bugs or errors in the software, but because of unclear text and ambiguous algorithms in the standard. For many years this has been an inconvenient truth in the world of noise prediction. At the Forum Acusticum congress in 2005, special focus was put on uncertainties while implementing noise prediction standards. More papers on quality requirements for software implementation were presented in the years following. This has all contributed to the new quality standard ISO 17534 in 2015. In TR3 (ISO/TR 17534-3) test cases and recommendations for implementation of ISO 9613-2 are described in detail. This should make ISO 9613-2 unambiguous and makes it straight forward to implement in software. But to what extend is this true, and will this approach work for other calculation standards such as CNOSSOS-EU?

This paper describes the experiences of DGMR, member of the ISO 17534 working group, while using the recommendations of TR3 for a fresh and new software implementation of ISO 9613-2. Based on the experiences, this paper makes recommendations for quality requirements of existing and future standards.

## 2 What to expect from ISO/TR 17534-3

The main goal of ISO 17534 is to minimalize the differences in calculated results of different implementations of noise prediction standards. To examine the effect of ISO 17534, 2 commercial software implementations were compared using the 19 test cases described in TR3. Both software packages have options to include or exclude the recommendations of TR3.

The comparison could therefore be made for 2 cases; with and without the recommendations of TR3. The results of the comparisons are shown in table 1.

**Table 1:** Absolute differences in dB for 2 software packages with and without recommendations of IS0 17534.

| Test case | With | Without |
|---|---|---|
| 1-10 | 0.0 | <=0.2 |
| 11 | 0.0 | 3.9 |
| 12 | 0.0 | 1.8 |
| 13 | 0.1 | 2.4 |
| 14 | 0.0 | 0.3 |
| 15 | 0.1 | 3.8 |
| 16 | 0.0 | 0.9 |
| 17 | 0.0 | 15.6 |
| 18 | 0.0 | 2.6 |
| 19 | 2.4 | 0.1 |

As displayed in Table 1 there is a significant positive effect when applying TR3. The large difference of 15.6 dB in test case 17 is now reduced to 0.0 dB. The reason for this is the new unambiguous rubber band method to calculate lateral detours. In ISO 9613 the left and right detours are in many cases unclear and ambiguous. One could choose to select the highest screening effect per individual screen or select the largest left and right detour. In TR3 the rubber band method is always used as shown in Figure 1.

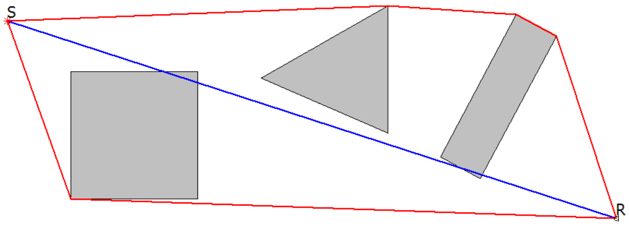

**Figure 1:** The red lines show the lateral detours using the rubber band method for test case 17

The exception of 2.4 dB for test case 19 is caused by a contradiction between TR3 and ISO 9613-2. According to TR3, in test case 19 there is a reflection contribution for 500 Hz until 8000 Hz octave bands. However according to ISO 9613-2 this reflection should only occur for the 8000 Hz octave band due to the low height of the reflecting facade in respect to the wave length. For 1 of the 2 software packages used in this comparison, the option to include the recommendations of TR3, obviously also de-activated the

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wave length criterion for the height of reflecting barriers. This omission has already been reported to, and acknowledged by, the ISO 17534 working group.

## 3 ISO/TR 17534-3, points for improvement

### 3.1 Nominal frequencies

In Chapter 1 of ISO 9613-2 it is stated that the calculations are executed with nominal mid band frequencies from 63 Hz to 8 kHz for the octave bands. However, in all test cases the calculations are performed for 62.5 Hz and not the nominal frequency of 63 Hz.

### 3.2 Speed of sound

In ISO 9613-2 the speed of sound is not given but only a note on how the calculation of the wavelength for the reflection criterion is calculated in which 340 m/s is used. The speed of sound however depends on the air temperature. One could use the same temperature which is used to select/calculate the air absorption.

### 3.3 Subdivision of line and area sources

Chapter 4 of TR3 states that line sources (including road and rail) are divided into line segments, area sources are divided into area segments, each represented by a point source at its centre. There are no rules given on how to do so. This indicates that the check “with automatic subdivision of line and/or area sources under consideration of the distance to the receiver” in Table 71 should be removed as it is not based on ISO 9613-2, unless it were added as an additional recommendation. There are only rules described for grouping point sources (same Lw and height, same propagation and d<2Hmax). This check is not included in table 71.

### 3.4 Wavelength criteria for screening obstacles

ISO 9613-2 states in Chapter 7.4 that an object is only considered to be a screening obstacle when its horizontal dimensions perpendicular to the source-receiver line is larger than the wave-length. It is not specified in TR3 if this requirement is used. Test calculations seem to indicate it is not used. In case of reflections this can quickly result in high barrier effect for only a small object, as (according to the recommendations) in reflection calculations only the vertical detour is taken into account.

### 3.5 Negative detour

The use of the rubber band method seems to indicate that no barrier effect will be calculated in case of a negative detour (the top barrier is below the direct line source – receiver). This is not ac-cording to ISO 9613-2.

### 3.6 Test cases T08, T09 and T19

In test case T08 the left and right detours are calculated. According to the factor 8 criteria of TR3 these should be omitted. In test case T09 the right detour is calculated. According to the factor 8 criteria TR3 this should be omitted.

In test case T19 a reflection is calculated in a barrier which is located on a slope and which length is larger than its height. It is only possible to replicate the results stated in TR3 when altering the model or calculation as follows:

1) The test case does not use the correct definition of lmin in formula 19. According to ISO 9613-2 the definition of lmin is “the minimum dimension (length or height) of the reflecting sur-face.” In this test case the value lmin is determined by the height of the barrier and not by the length, thus, reflections are only possible for 8000 Hz.

2) If this height criterion is ignored and only the length criterion is used, the test case still does not give correct results as no reflection is calculated for 250 Hz. This seems to be the result of add-ing a node to the barrier where it crosses the height line at the bottom of the slope and thus shorten-ing the length of the barrier.

## 4 Conclusion

The ISO 71534 standard fulfils its aim. The differences in results between separate software applications for the same situation are strongly reduced. A similar positive affect can be expected when using this approach for CNOSSOS-EU. The ISO/TR 17534-3 report does contain some obvious errors, conflicts with ISO 9613-2 and unclear text. These could easily be fixed in a new revision. ISO/TR 17534-3 is more than a recommendation on how to interpret ISO 9613. It could be consider as a new method. So there are now 2 methods: ISO 9613 and ISO/TR 17534-3. This might lead to confusion

## 5 Recommendations

Replace ISO/TR 17534-3 by a review of ISO 9613 that includes the recommendations and test cases of ISO/TR 71534-3. This will make ISO/TR 71534-3 obsolete. Fix the issues as discussed in paragraph 3. Make clear choices. For instance state that the method is not suited for area sources and line sources or, add a clear unambiguous algorithm on how to do so. This recommendation also applies to any other existing or future standard.

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# EVALUATION ON OVERLAPPING BARRIERS DESIGN USING SOUNDPLAN

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## 1 Introduction

Traffic noise comes along with highway and city road developments. As these roadways are being built closer and closer to residential areas, residents will be exposed to higher or even intolerable noise levels. To overcome traffic noise problems, solutions such as noise barriers, low noise pavements, low noise vehicles, traffic control measures, and proper land uses have been proposed.

Due to being considered to have great benefits of easy installation, better noise reduction performance, and ability to soothe annoyed residents, noise barriers have become the most prevalent noise control measures adopted by most agencies. However any defects in noise barriers may allow unnecessary noise propagation and thus degrade their performance. Consequently, noise barriers should be constructed and maintained with care to uphold their designed noise reduction capability.

Ideally, noise barriers would have no breaks at all. However, few barriers can be designed without the need for a break in the wall. Breaks in noise barriers are needed for many reasons, such as maintenance, safety access, drainage, and barrier transitions between different roadway sections. When these breaks are necessary, overlap gaps are often used to lessen the effect of the discontinuity, but inappropriate design may cause severe degradation of acoustical effectiveness, and therefore, acquiring the appropriate parameters of the overlapping barrier design will serve as a reference for decision makers to properly allocate the gap location and select the sound design.

This analysis focuses on the evaluation of overlapping barrier design and receiver regions in the vicinity of an overlap gap. Noise attenuation performance of overlapping barrier from road traffic noise was investigated using the FHWA TNM version 2.5 module in SoundPlan v7.4 computer program, which not only corrects known deficiencies in the TNM algorithms, but also considers the reflection effects of the barrier [1,2]. The contributions from various parameters such as materials, barrier height, gap, and overlapping sizes were investigated.

## 2 Gap geometry and propagation paths

The possible paths through which noise may propagate to a receiver at an overlap gap situation are: direct propagation, transmission, simple diffraction, double diffraction, multiple reflections, and multiple reflected diffractions.

In order to study the effect of overlap gaps on the surrounding area, a simplified noise model was created as per the typical overlap gap configuration, which is represented in Figure 1. The traffic noise source is taken to be the center of road. Receivers being investigated can be located within the gap or more typically on the opposite side of the barrier from the source. Due to the complications of sound propagation mechanism, a number of simplifications, assumptions, and/or limitations were used in the development of the noise model. All barriers were considered to be parallel to the line of the road with a typical height of 1.8 m, which is similar to a regular private fence. Ten reflection orders were considered to be sufficient reflection inside the gap area. Ground is assumed to be typical lawn area. The road was modelled as 1000 vehicles per hour with 110 km/hr speed. The area was assumed as flat. The barrier materials were considered as five types of absorption, which includes totally reflective, smooth façade, structural façade, absorptive material and highly absorptive material (each with corresponding reflection loss 0, 1, 2, 4, 8 dB, named as RL 0, RL 1, RL 2, RL 4, RL 8).

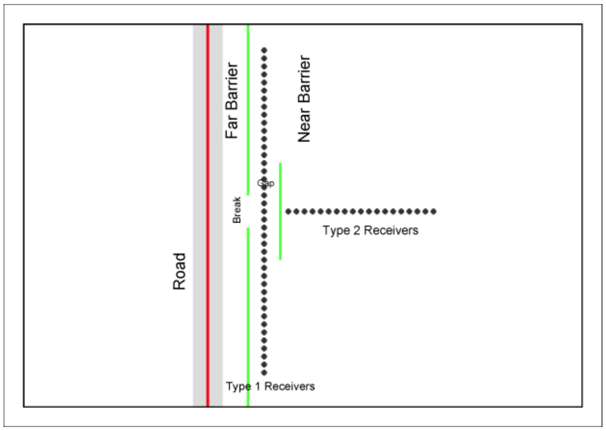

**Figure 1:** Typical overlap gap configuration

There are certain design characteristics that must be considered to ensure a barrier's optimum performance. The barrier must be sufficiently long so that the receiver is protected from edge diffraction. Edge diffraction is the propagation of sound waves around the ends of a noise barrier. If a barrier is extended a reasonable distance past any potential receiver, edge diffraction is considered to have minimal effect on the noise level. In addition, the noise barrier must be constructed from a solid material of adequate density with no cracks to prevent noise from transmitting directly through the barrier. With that considered, the effectiveness of a noise barrier depends directly on its length and its heights with respect to the source and receiver locations.

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## 3 Barrier performance investigation

### 3.1 Single barrier performance

In order to provide a basis to judge the effectiveness of an overlap gap design, insertion loss of a single barrier is investigated. First, an analysis was done on the single noise barrier to determine the noise levels at a receiver's position without the break, and different absorption types. Figures 2a and 2b show that sound attenuation of the single barrier related to the barrier absorption for the two types of receivers. The results indicate that barrier absorption benefit is minor in this single barrier scenario, which is usually less than 1 dB additional insertion loss.

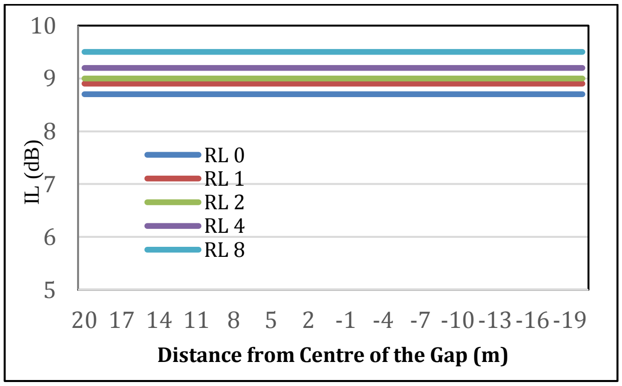

**Figure 2a:** Sound attenuation of the single barrier related to the barrier absorption for type 1 receivers

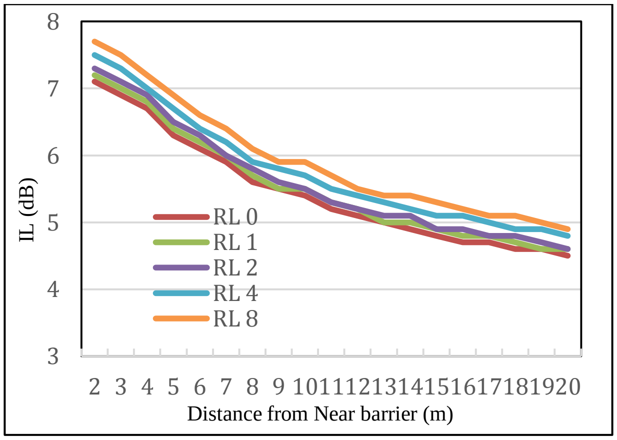

**Figure 2b:** Sound attenuation of the single barrier related to the barrier absorption for type 2 receivers

### 3.2 Overlapping gap barrier

To reduce the negative effect that this gap has on the noise environment, the ends of each barrier are extended past one another to form an overlap. This blocks line-of-sight propagation for most propagation paths. The amount of overlap is often selected to reduce the levels of noise flanking around the ends of the barriers to the point that the noise diffracting over the top of the barrier becomes the dominant noise at the receiver.

The primary problem with installing an overlap gap is the introduction of reflective sound waves. By overlapping the near and far barriers a sufficient distance, the line-of-sight is broken between the traffic and most receivers; and therefore, the majority of direct rays are eliminated. However, reflected rays exist regardless of the length of the overlap. Absorptive treatment is commonly used on parallel noise barriers to prevent reflections from causing insertion loss degradation.

Research has been conducted to study the effectiveness of using absorptive panels to minimize reflections at overlap gap barriers. Insertion loss is investigated with different absorption type inside the gap surfaces. The results for the type 1 receivers show that a higher absorption inside the gap is efficient to attenuate the noise, and the overlapping length should be at least the same length of the break size. Figure 3 shows the results with this typical gap design.

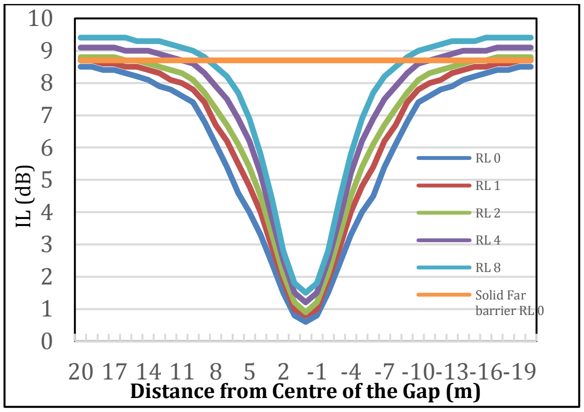

**Figure 3:** Sound attenuation of the overlapping barrier related to the barrier absorption

The results indicate that the insertion loss with the absorption can be less than 2 dBA at the gap end of the overlapping barrier, compared to a far barrier with no break.

## 4 Conclusion

This study first investigated the solid barrier performance with the absorption and insertion loss degradation with break. The results showed that an absorption benefit for the barrier performance is minor, which is usually less than 1 dB additional insertion loss.

For this scenario, the overlapping length should be at least the same length of the break size with this typical overlap gap design, which means the total length of the near barrier would be 3 times of the break size. The results indicate that insertion loss with the absorption can be less than 2 dBA at the gap end of the overlapping barrier, compared to a barrier with no break.

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# TRADING DECIBELS: OVERVIEW OF A CAP AND TRADE REGULATORY FRAMEWORK FOR NOISE EMISSIONS

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## 1 Current regulatory framework and its shortcomings

Noise for energy-related facilities in Alberta is regulated through the Alberta Energy Regulator (AER) Directive 038: Noise Control (the Directive) [1]. The goal of the Directive is to reduce the impact of noise received in the environment to a reasonable amount. In its simplest case, the Directive sound level limit is 40 dBA, as measured at the nearest or most impacted residence within 1500 m of a facility. If no residences exist in that zone, then the limit is set at a 1500 m distance. If the facility sound levels are below the limit, then the facility is in compliance, and if above the limit, then the facility is out of compliance. While this approach meets the goal of reducing the noise impact at the receiver to a reasonable level, it still has some shortcomings:

i. No incentives to maximize margin of compliance beyond the Directive criteria: In some cases, additional margin of compliance is easily achieved with minimal efforts/expense incurred by the facility owners, and a reasonable investment of noise control can often yield significant benefits in further reducing noise impacts.
ii. Inefficiency in Retrofit Noise Control: With a facility operating at the regulatory limit for noise emissions, facility expansions (and/or new proximate facilities) creating additional sound power will often require exceptional noise control (for new equipment), retrofit noise control (for existing equipment), or both. Many industry operators report that retrofit noise control costs can easily exceed ten times the initial capital cost for the same noise control included at the design stage.
iii. Little incentive to advance noise control technology: As technologies employed in equipment operation advance and mature over time, it is expected that low noise-emitting equipment becomes more easily available and at a lower cost. However, since the Directive sound level limit is static, there often exists an incentive to deploy equipment that simply meets the limit, rather than installing the latest low-noise-emitting equipment that would optimize the margin of compliance.

## 2 The principle of cap-and-trade, and its potential use in noise emissions

Cap-and-Trade programs impose a limit on emissions (e.g. noise) within a given area. Emitters within the area are given allowances (e.g. sound power) to emit within a given timeframe.

Over time, a governing authority may choose to reduce allowances: this reduces overall emissions (e.g. cumulative noise) within the area. To remain compliant, an emitter must either reduce emissions (e.g. install noise control) or purchase additional allowances in open-market trading in order to continue operating at the same emission rate. However, if an operator emits below their allowance limit, this generates an emission credit that could be sold to others. The supply/demand balance of available allowances and credits dictates market value, which ultimately guides the timing, choice of source, and noise control technology best suited for noise reductions.

## 3 How a cap-and-trade program can overcome the shortcomings

i. No incentives to go above and beyond the Directive criteria: The Cap-and-Trade program creates both a positive incentive for achieving high margins of compliance and a negative incentive for deferred adoption of reasonably noise-controlled equipment. The positive incentive is created by the facility owners generating credits, if they operate equipment with noise emissions below its reasonable PWL value. This credit could be sold or transferred to other facilities with equipment noise emissions that do not meet the reasonable PWL. The negative incentive is created by the facility owner's requirement to purchase credits if they operate equipment with noise emissions exceeding its reasonable PWL value. It is therefore in the company's interest to evaluate if it is more cost-effective to obtain facility equipment which meets the reasonable PWL, or else purchase credits from other companies. This offers facility operators more alternatives to optimize compliance for minimal cost.
ii. Inefficiency in Retrofit Noise Control: As the Cap-and-Trade assessment will occur during the facility design stage, it will help to avoid the problem of costly retrofit noise control, because there now exists an incentive to install equipment that is below the reasonable PWL at the design stage. As such, the facility sound levels received in the environment around the facility will not approach the Directive's regulatory limits as quickly. This will leave acoustic room for further facility expansions in the same area, rather than incentivizing facilities to disperse to other green field areas.
iii. Little incentive to advance noise control technology: The "reasonable PWL" criteria of a given type of equipment are determined by taking population

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measurements of that same type of equipment currently operating at existing facilities. As technology improves and more low-noise equipment is installed and operated over time, the criteria value will naturally decrease proportionally. A particular facility owner can lead the trend by being proactive, or else follow the trend that other companies establish. This creates a continuous improvement mechanism where, as the facility owners adopt available technologies for low-noise equipment, their actions will in turn further advance the technology and lower costs.

## 4 Example: hydraulic drivers

An engine skid hydraulic driver (driver) is a unit composed of a gas engine and hydraulic pump, which drives a screw pump located in an oil well. Although these units are available in a wide horsepower range, for a given horsepower, the unit comes as a typical package, and as such, is a good candidate to classify as a distinct type of equipment that can have a "reasonable PWL" criterion.

The first step is to determine the "reasonable PWL" criterion. This is achieved by measuring several units of that type, from different packagers, and purchased by different facility owners. Once sufficient data points are gathered, then the average PWL values (or other statistically-validated limit) become the value for the "reasonable PWL" criterion.

Over time, as a facility owner plans to install additional equipment at a facility, the procured equipment PWL will be evaluated against the "reasonable PWL" criteria. If an equipment PWL exceeds its individual criterion, then the facility owners would be required to purchase noise credits in order to install higher-than-average noise-emitting equipment. If an equipment item is below its criterion, however, then the facility owners will generate noise credits as a reward for installing lower-than-average noise emitting equipment.

Facility Owner A plans to install 75 hp drivers at a facility, and decides to spend a bit more money to obtain lower-than-average noise-emitting equipment. Consequently, they generate cap-and-trade credits. They can then transfer these credits to one of their other facilities, if needed, or else sell them to another facility operator. Facility Owner B plans to install 75 hp drivers at a facility and decides to reuse old models they have in stock. As these models are old, they have higher-than-average noise emissions and exceed the current "reasonable PWL" criteria. Consequently, Facility Owner B would be required to obtain cap-and-trade credits, either through transfer from another facility, or through purchase in an openly-traded market (from someone such as Facility Owner A).

As a result, Facility Owner A has achieved a high margin of compliance, below the Directive criteria, instead of simply meeting the regulated limits at the receivers. By purchasing lower-than-average noise emitting equipment, they help to advance the adoption of emerging technologies, and they also obtain noise credit revenues to help offset incremental costs for quieter equipment.

## 5 Limitations to the cap-and-trade program for noise emissions

Before the program can be implemented, a critical milestone will be determining the values of the "reasonable PWL" criteria for different types of equipment. This could be obtained by calculating the average PWL value of all the existing equipment PWL measured in the field, or using another statistically-validated limit. A sufficient quantity of field measurements must be gathered to reach an adequate level of confidence that the resulting average is representative of the current equipment population operating in the field.

Each particular type of equipment's "reasonable PWL" criteria must be thoughtfully defined with sound engineering judgment (e.g. normalized to a relevant metric, such as driver horsepower), in order to fairly determine the correct criteria against which proposed equipment will be compared. For example, a proposed 75 hp driver should be compared against the 75 hp driver criteria, not against the 40 hp driver criteria.

## 6 Conclusion

Historically, Cap-and-Trade programs have been most effective for reducing regulated emissions when there exists adequate market liquidity to ensure fair and reasonable market pricing. In other words, there must exist a sufficient numbers of buyers and sellers of allowances and credits. In the case of noise, this requires an adequate number of noise sources – which is certainly present in an urban environment, but could also be present in a congested rural environment (i.e. several proximate facilities). The authors emphasize that they are not suggesting that more regulation is a solution; rather, they offer that Cap-and-Trade programs for noise emissions could provide a means, in certain regions, to reward operators with a high social license, helping them to monetize some of their noise control investments that achieve high margins of compliance below regulated limits for noise.

## Acknowledgments

The authors wish to acknowledge Patching Associates Acoustical Engineering Ltd. and the clients and industry peers who offered insights and experiences that shaped this paper.

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# STANDARD METHODS AND CRITERIA CONSIDERATIONS FOR RESIDENTIAL NOISE COMPLAINTS

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## 1 Introduction

Acoustic consultants receive many inquiries about noisy neighbours, particularly from occupants of multi-unit residential buildings. There are currently no standards or regulations that objectively define thresholds for what is considered an annoyance or unacceptable noise intrusion. Noise intrusion can diminish quality of life, increase stress, and interrupt sleep. Long-term health effects are also likely (WHO [1]) without considering additional stress from conflict with a neighbor.

Legal counsel is often sought, which can be futile without standard criteria. The only reprieve for most chronic noisy neighbour problems is attained when someone moves.

The intent of this paper is to review the literature, outline major components for consideration in the development of a standard procedure and criteria, and recommend a standard method and criteria for discussion.

## 2 Literature review

### 2.1 Canadian codes and by-laws

The 2010 National Building Code of Canada (NBCC) [2] has been either fully or largely adopted by all of Canada's provinces. The only acoustic requirement of the NBCC is for dwelling 'separation' construction. Current provincial codes reference the 2010 NBCC which requires a minimum STC 50 between adjacent units. The 2015 NBCC [3] has been revised to a minimum requirement of ASTC 47 between dwelling units, which is likely to be adopted in future versions of provincial building codes.

In both cases (STC and ASTC) the focus is on element construction with no published discussion about assumed activities and noise levels (talking, sound systems, etc.) or background noise levels, which are both critical components to the full discussion on neighbourly annoyance and peace.

Many Canadian by-laws limit sound intrusion at the property line in residential areas to 55/45 dBA for day/night-time or they have a 'shall not disturb the peace and quiet of neighbours' type of statement. The by-laws are largely limited to exterior property lines and steady or pseudo-steady (repeated) sounds such as dogs barking.

### 2.2 Guidelines

The Canadian Mortgage and Housing Corporation (CMHC) advocates on behalf of Canadian tenants and homeowners, publishing many research-based guidance documents.

Most of their acoustic documents relate to environmental and building services noise; however, Morin and Guerin [4] suggest a protocol for assessing and rating the acoustical comfort of a building based on several factors. For fluctuating or transient noise sources (elevators, garbage chutes or plumbing), they recommend limiting $L_{max,imp}$ to below NC 20. The Facility Guideline Institute (FGI [5]) recommends an hourly $L_{eq,slow}$ of 45 dBA and an L10 of 50 dBA with a transient sound limit of 65 dBA $L_{max,slow}$ for sleep areas in hospitals.

The World Health Organisation (WHO) [1] suggests that an internal $L_{eq,fast}$ of 30 dBA is needed to prevent negative effects on sleep and health. For non-continuous noise, sleep disturbance correlates best with $L_{max,fast}$ with effects observed at 45 dBA or less. They suggest that the number of $L_{max,fast}$ events (not to exceed 10-15 per night over 45 dBA) and the difference between $L_{max,fast}$ and $L_{eq,fast}$ levels must be taken into account. Lower limits are recommended for sensitive people. WHO also state that indoor noise during the daytime should not exceed an $L_{eq,fast}$ of 35 dBA to limit annoyance to 'moderate'. To address low-frequency noise, WHO recommend a frequency analysis and lower limits if the difference between dBA and dBC is greater than 10 dB.

The WHO Night Noise Guidelines for Europe [6] suggests that an indoor $L_{max,fast}$ of 45 dBA is likely too high for limiting sleep disturbance, based on newer research.

### 2.3 Scientific community

The authors were unable to find published research that specifically addresses the problem of noisy neighbours.

Park and Bradley [7] provide an indication of level of annoyance relative to various noise metrics. They found reasonable correlation between annoyance and the simple A-weighted signal-to-noise ratio (SNR(A)) for both music and speech. They recommend modifications to many conventional assessment methods, including the SNR(A), to improve correlation with annoyance. The study indicates that people become 'moderately annoyed' when the SNR(A) is approximately 2 dB for speech and music.

## 3 Considerations for a standard assessment

### 3.1 Source, receiver, and transmission path

The critical components in a noise annoyance study are the source, transmission path, and receiver.

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Common sources are raised voices, footsteps, children, pets, TV, music (including via subwoofers), intimacy, musical instruments, construction, building systems, and cooking (banging of pots, pans, cupboards, or dishes). People vary in awareness of the effect of their activities, their concern for others, and/or their right to enjoy their own space as they please.

Common receiver activities are sleeping, reading, focused work (computer work), meal times, watching TV, and cooking. The time of day and demographics (coupled with expectations) can significantly affect the response of receivers. Background noise levels in a receiver dwelling can make intrusive noises more audible if too low.

Canadian building codes address the transmission path based on assumptions of source levels (regular talking, TV) and background noise levels in the receiver space (30 dBA). These assumptions have no longer kept up with society as sub-woofers and low (<25 dBA) interior background noise levels have become more commonplace.

### 3.2 Assessment measurements

Most intrusive noise sources that garner complaints are intermittent, ranging from relatively predictable or completely random with respect to time of day, frequency of occurrence, and duration. Measurements will be either short-term attended or long-term unattended. Short-term measurements can be time consuming and may not capture an event, but provides the benefit of witness to the events. Long-term unattended monitoring is more likely to capture the offending sounds, but requires recordings to confirm noise sources; however, recordings compromise privacy for residents, if they are present during monitoring.

### 3.3 Metrics and criteria

The intent of sound measurement metrics are to provide a simple numerical representation of how the average person is expected to respond to a particular sound. Some things to consider (in combination) include: integration time (slow/fast/impulsive/peak), measurement duration/averaging time (1 s to 24 hr), level type ($L_{max}$, $L_n$, $L_{eq}$, SEL), event definition (level, number, duration), frequency (broadband, octave band, 1/3$^{rd}$-octave band, narrow-band, and the frequency range included in each), and tonality (directly or indirectly).

If the metric(s) chosen are appropriate, then criteria become easier to define. Criteria should consider: levels, definition of day/night, events (level, quantity, duration), background levels, intermittency, and character (tonality).

## 4 Recommended method and criteria

Measurements must be taken in an unoccupied space with a ‘Type I’ sound level meter in the ‘fast’ setting, can be attended and/or unattended, and should include recordings for post-processing and source verification of events. The metrics and criteria provided in Table 1 should be met in all 1/3$^{rd}$-octave bands from 50 Hz to 10 kHz for both airborne and impact noise intrusion.

**Table 1:** Proposed noise intrusion assessment criteria

| **Evaluation Metric (in each 1/3$^{rd}$-octave band from 50 Hz to 10 kHz)** | **Daytime (7am to 9pm)** | **Nighttime (9pm to 7am)** |
|---|---|---|
| $L_{eq,1hr}$ | $L_{90,1hr}$ +2 dB | $L_{90,1hr}$ +2 dB |
| $L_{max}$ threshold ($L_{MT}$) | $L_{90,1hr}$ +12 dB | $L_{90,1hr}$ +12 dB |
| # $L_{MT}$ exceedances allowed | 28/day* | 10/night* |
| # $L_{MT}$+5 dB exceedances | 14/day* | 0/night |

*Note: Cumulative number of events inclusive of all 1/3$^{rd}$-octave bands

The basis of the proposed assessment criteria is a signal-to-noise (SNR) ratio that uses $L90_{1hr}$ to represent the interior background sound level (i.e., ‘noise’) with allowable ‘signal’ levels based on Park and Bradley [7] ($L_{eq,1hr}$), and WHO [1] ($L_{max}$ and number of exceedances). Using SNR provides dynamic criteria that are expected to align well with perception and annoyance.

Further, our experience has demonstrated that simplification to broadband metrics is insufficient for evaluating noise intrusion issues because background and intrusive sound spectra often differ significantly. We have therefore recommended evaluation in 1/3$^{rd}$ octave bands.

## 5 Limitations and intent

This paper outlines many of the considerations around residential noise complaints, but excludes the practicality and complexities related to political, social, economic, market, and other forces that would influence and be influenced by the intended standard criteria.

The intent of the proposed standard criteria is to hold neighbours accountable for the noise they create, regardless of construction (i.e., if noise transmits easily, extra care is required).

A further goal of this paper is to initiate the future development of an appropriate national or international standard criteria and method for assessment. Further research to confirm the proposed metrics and criteria are expected.

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# SOUND POWER LEVELS AND DIRECTIVITY PATTERNS OF REFRIGERATED TRANSPORT TRAILERS

**Jessie Roy** [*1] **and Peter VanDelden**[†2]
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## 1 Introduction

Refrigerated transport trailers are part of the daily operation of many food processing facilities, distribution centers, grocery stores and some pharmaceutical facilities. Refrigeration units mounted on the front of the trailers are used to maintain the trailer temperature. An example of a refrigeration unit mounted on a transport trailer is pictured on the left-hand side of Figure 1.

The type of refrigeration unit described in this paper is autonomous, typically comprised of a diesel engine, a compressor, a condenser and an evaporator. The most common manufacturers, Carrier and Thermo King, each have several models. They are generally constructed with one or more fresh air intakes at the front or side. Heat rejection and combustion exhaust are emitted from the top. Each of these primary sound emission locations is shown in Figure 2. This paper treats the unit as a single source rather than separating each of the emission points.

One of the challenges with including this type of equipment in facility noise models is that the specific model and manufacturer of refrigeration units can vary on a day-to-day basis. Manufacturer data can also be difficult to obtain or is unavailable. The trailers at the facility often are operated by a shipping or logistics company instead of the facility owner. In such cases the benefits of any specific model of refrigeration unit (e.g. low noise package) cannot be reliably used in predictive modelling.

Detailed sound power data for this type of equipment are also infrequently available. Generic or average sound power information is of value in these circumstances. This paper presents a summary of measured sound power levels and directivity patterns for refrigerated transport trailers based on measurements conducted by RWDI between 2003 and 2016.

## 2 Method

The sound power levels presented in Table 1 have been calculated from sound pressure level measurements of sixteen distinct refrigeration units collected between 2003 and 2016. In each case the unit was operating without a truck connected to the trailer, while the trailer is parked at a loading dock or in a parking lot. Situations where a refrigeration unit was close to other sources were not included in this analysis. The surface of the ground in all cases was considered to be hard and reflective. The sound from the front of the unit has the highest overall level and has been used to develop the average sound power level.

The source directivity in the horizontal plane was quantified at facilities where sufficient space was available. Sound pressure levels were collected at multiple angles from the refrigeration unit. For documenting directivity, we are defining zero degrees as straight out from the refrigeration unit (e.g. directly in-front of the refrigeration unit), and ninety degrees as perpendicular to the direction of travel of the transport trailer.

**Figure 1:** Example of a refrigerated transport trailer

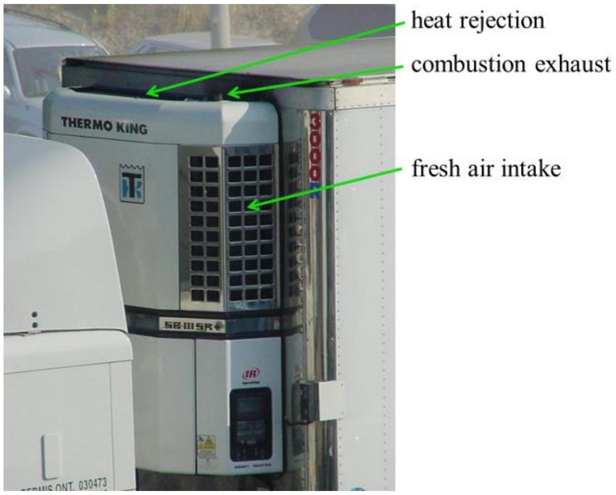

**Figure 2:** Primary sound emission locations

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**Table 1:** Average sound power level and standard deviation

| | Frequency (Hz) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 31.5 | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| Average | 97 | 111 | 105 | 102 | 97 | 96 | 94 | 89 | 83 |
| Standard Deviation | 3.7 | 4.5 | 5.5 | 5.5 | 5.0 | 5.5 | 5.1 | 5.4 | 6.1 |

# 3 Results

## 3.1 Octave band sound power levels

The average sound power level from in-front of the refrigeration units is 102 dBA, with a standard deviation of 4.7 dB. Variation in manufacturer, model and operation setting contributed to a range from 93 dBA to 109 dBA. The average linear octave band sound power levels from in-front of the refrigeration units and standard deviations are shown in Table 1. The octave band sound power level data are presented in Figure 3.

## 3.2 Directivity

The sound from refrigeration units does not project uniformly in all directions. To present directivity consistently we have normalized the levels at angles other than zero degrees to the sound power at zero degrees for each unit. The directivity has been assumed to be symmetric along an axis along the length of the trailer, with the zero angle defined as the direction of normal trailer travel. An average directivity pattern is proposed in Table 2. The directivity for non-zero angles is based on a smaller sample set, but indicates a general trend.

**Table 2:** Average directivity pattern

| Angle | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| 0° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45° | -5.3 | +2.7 | +1.9 | +1.1 | +0.2 | -1.0 | -1.0 | -1.1 |
| 90° | -7.5 | -5.1 | -3.1 | -1.1 | -2.6 | -3.5 | -3.9 | -4.5 |
| 135° | -2.3 | -4.7 | -4.8 | -2.8 | -6.0 | -8.2 | -10.4 | -11.2 |

# 4 Discussion

Sound from the refrigeration units show a large variation in level from one unit to another. However, the spectral shape is relatively consistent for all of the units measured at zero degrees. From Figure 3, it can be observed that for most of the units tested the 63 Hz band is dominant; however, this does not necessarily mean that the sound is tonal. As an internal combustion engine, the concentration of sound at 63 Hz covers a wider range of frequencies.

Some of the units show elevated levels at both the 63 Hz and 125 Hz octave bands. Factors influencing this characteristic and the overall sound level were not readily apparent. Information on factors such as the number of years the equipment had been in service, operating settings, and whether the manufacturer's low noise package was installed (if one was available) were not available for the units measured, but would be interesting to examine in future studies.

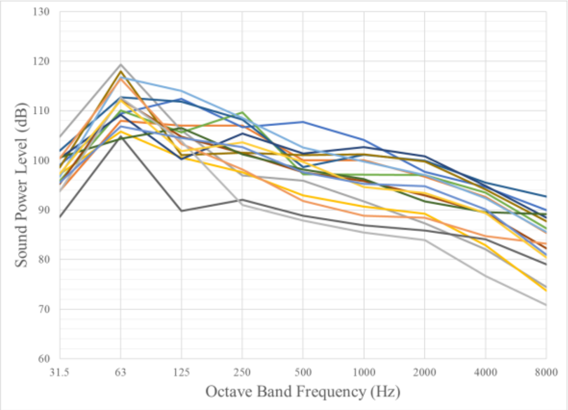

**Figure 3:** Trailer refrigeration unit sound power levels

As shown in Table 2, the sound levels generally decrease at angles away from zero degrees. The average directivity pattern should be primarily considered indicative of a trend. Additional data sets should be considered to develop a more definitive directivity pattern.

The adoption of standards and certification schemes for rating noise emissions of transportation refrigeration equipment, such as AHRI 1120 [1] in the United States, NFR 10-304 [2] in France, DIN 8958 [3] in Germany, and the PIEK certification scheme [4] (which originated in Holland and has been adopted in several other countries) are improving the availability of sound power data for new transport trailer refrigeration equipment. Nevertheless, documentation is still typically limited to only an overall A-weighted sound power level rating on most North American new product documentation.

# 5 Conclusion

Octave band sound power levels for sixteen different transport trailers' refrigeration units are developed into an average sound level spectrum. The spectrum is generic in that no differentiation between manufacturer, feature or operating condition is provided. The spectral shape is relatively consistent for all of the units tested at zero degrees, the typical direction of travel. At frequencies above 500 Hz, the sound levels show a pattern of becoming quieter with increasing angle.

# References

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# A BARRIER FOR COMMUNITY POWER GENERATION CLOSE TO HOMES

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## 1 Introduction

Urban intensification can result in a loss of buffer zones, placing sources of noise and sensitive points of reception in closer proximity to each other and increasing potential for conflict. Complete removal of separation distance that is used for sound reduction can require replacement with substantial mitigation measures.

This case study looks at challenges encountered in achieving acoustic separation between a community power generation facility and neighbouring residential development lands. Characteristics of the sites and local topography combined to require use of a tall sound barrier. Installation of the barrier allowed residential land use on property immediately adjacent to a community power generation facility.

## 2 Background

Sloping topography characterizes the community power generation facility site and residential development site. Figure 1 provides a plan view of the area. The development land slopes upwards quite uniformly towards the road, with a grade difference of about 10 m. The facility is on a flat area a few metres above the lower elevation of the development land and is bordered by steep upward slopes on the development and road sides. A swale or ditch runs at the base of the steep slopes. A row of tall, mature conifers is situated along the property line between the sites. Layout of the site is shown in Figure 2.

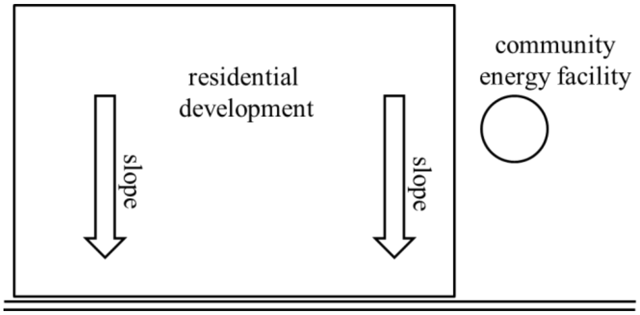

**Figure 1:** Residential development and facility

The residential development is a combination of single detached, semi-detached and row housing, except for a multi-storey building at the corner of the road and demising property line. The multi-storey building is thus placed at the highest part of the development.

For this area the acoustic separation requirements between industrial and residential uses requires cumulative sound from all sources on the facility site to be no higher than 45 dBA at the residential uses during nighttime hours.

Since the facility produces electricity, it operates at any time of the day or night. The three internal combustion engines that it uses are powered by biofuel. Unused biofuel is burned in an enclosed flare. The flare is constructed with the combustion occurring inside the base of the stack. The primary sources are therefore the internal combustion engines, aerial coolers, a compressor and a flare. The internal combustion engines had existing silencers.

Facility operation was predicted to result in sound levels of up to 60 dBA at the nearest residential parts of the adjacent subdivision, requiring an overall reduction of 15 dB to achieve the required 45 dBA limit. Approximately 40% of the development lands had facility sound levels above 45 dBA.

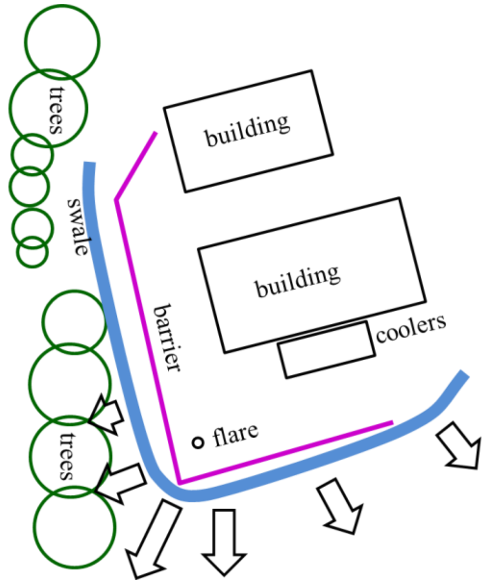

**Figure 2:** Community power generation facility site

## 3 Mitigation

Preventing residential development on a large portion of the land was not considered a suitable means of ensuring acoustic separation. Mitigation at the sources with or without use of a noise barrier was considered. The sources would have required upgraded combustion exhaust silencers and some large new silencers. However application of a silencer to the enclosed flare was needed and would have required special safety approval, would have incurred substantial cost and had the potential to degrade the flare performance. The idea of a silencer on the flare was set aside in consideration of the long time required for the

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approval process and lack of certainty that approval would be granted. Focus therefore shifted to use of a barrier.

To limit the height of the barrier, some restrictions were placed on the development. In particular, the multi-storey building would need to be constructed so that noise-sensitive parts of the building were not exposed to sound from the power generation facility at levels above 45 dBA. This could be achieved by some combination of setbacks of the building, height limitation or orientation of the sensitive faces away from the power generation facility. Specific details of the building were not worked out as the building concept was not sufficiently developed.

## 4 Challenges to use of a barrier

Finding a location for the sound barrier posed a number of challenges. Locating the barrier along the property line had the disadvantage that the adjacent residences would be overshadowed by a large wall. The row of tall conifers along the property line was desirable to create a visual screen between residences and the facility. Neither was it suitable to place the barrier on the slopes between the facility and property line. A barrier location directly adjacent to the facility could be achieved as long as access separations were maintained and drainage was not impeded. However, the large grade difference between the level of the facility and parts of the residential land required substantial additional barrier height. A location as shown in Figure 2 was finalized. The required height of the barrier was more than 13.5 m. This location would retain the trees as a visual screen to the barrier.

The concept and location then proceeded to detailed design. Extra civil and structural engineering were required because geotechnical information about the location of the barrier was unknown, and a barrier height of 13.5 m was higher than previous Durisol installations. The proposed location of the barrier was over soil that had been previously disturbed and had unknown properties. Neither the materials comprising the subsurface nor the level of compaction were known. This information was needed to determine the capability of the soil to support a tall barrier and the corresponding sub-surface depth of the posts and footing for the barrier. Geotechnical testing was therefore conducted. Properties of the subsurface materials at this location required footings of almost 5.5 m depth.

Together with the analysis for sub-surface support of the barrier, the work for structures above the surface needed to consider wind loading. Loading required additional strength of the structural members. Final design provided larger and additional beams on the lower portion of the barrier, as shown in Figure 3. The addition structure required was hidden from view of the residences by locating it only on the facility side of the barrier.

**Figure 3:** Facility side of noise barrier

## 5 Verification

Effectiveness of the barrier was evaluated by measurements after construction. Direct comparison with the 45 dBA limit was not possible during the measurement period because the facility was unable to operate at full capacity. The sound level from the facility was therefore compared with modelling.

Sound level measurements were conducted at the location with highest modelled sound level based on actual operating conditions of the facility with the barrier in place. Measurements were conducted during nighttime hours when background sound from other human activity was minimized. Sound at the measurement location included some human activity and the sounds of nature. This non-facility sound was therefore measured at an acoustically equivalent location away from the facility. The two measurements were conducted immediately after each other so that the background sound would be as similar as possible. The net facility sound level of 35 dBA at the measurement location was below the modelled level of 41 dBA and indicates that the barrier performs acoustically at least as well as expected.

## 6 Conclusion

In this case the buffer zone between a community power generation facility and adjacent residential land use was successfully replaced with a sound barrier that is taller than previously constructed by Durisol. Some of the associated challenges associated were overcome by geotechnical testing and maintaining a visual screen provided by an existing stand of mature trees. The barrier performed at least as well as expected.

Implementation of the barrier allowed the developer to achieve full utilization of the site, fulfilled the electricity generator’s vision of being in the community rather than isolated from it, and allowed the municipality to maximize residential development.

# ABSTRACTS FOR PRESENTATIONS WITHOUT PROCEEDINGS PAPER
# RÉSUMÉS DES COMMUNICATIONS SANS ARTICLE

## Outdoor Concert Noise: The Kitchener On Experience

*Lucas Finlay Arnold, Darron Chin-Quee, Scott Penton*

Outdoor music festivals have the potential to cause adverse public reaction and noise complaints, particularly from surrounding residential neighbourhoods. At times, seemingly random noise complaints occur, with clusters of complaints occurring in areas well removed from the venue, while adjacent nearby neighbourhoods experience little to no noise. This paper examines the experience in Kitchener, Ontario with The Ever After Music festival, a three-day electronic music festival run in the City since 2015. In its inaugural year, the festival prompted 57 noise complaints, with 7 the next year in 2016, and approximately 100 alone on the final concert night of 2017. Efforts of the promoters and the City to reduce noise impacts, including controls that were put in place, are reviewed and compared to those used in other jurisdictions. Potential event specific relationships between complaint locales, weather, and meteorological effects are also reviewed, as determined through noise propagation modelling and where available, measured sound levels.

## Estimating Hourly Leq From 24 Hour Leq

*Miranda Lynn Daly, Tim Kelsall, Hicham Khelladi*

The Average Annual Daily Traffic (AADT) for a given area can be used to determine 24 Hour Leq equivalent sound levels near roadways and in the community. This does not give an indication of how the L-eq- changes through the day. Many jurisdictions, like Ontario use Leq1h as a common descriptor. During a recent project, measurements were taken in residential communities, including next to highways and commuter rail lines and the differences from the 24 Hour L-eq- were calculated for hourly Leq throughout the day. When averaged, these values can be used as correction factors to help to approximate hourly Leq values -based on an Leq,24h calculated from AADT data.

## Brief History Of Montreal Noise-Bylaws And Their Enforcement

*Romain Dumoulin*

The City of Montreal noise by-laws, in their current state, can be traced directly to the "Règlement sur le bruit - No 4996", first enforced in 1976, following the pioneering research and field work of Jean-Gabriel Migneron on urban acoustics. From the first City by-laws concerning public peace and order in 1865 to the latest noise by-laws modifications that differ from borough to borough, this talk traces the development and evolution of the noise-bylaws in Canada's second largest city. It provides an historical background, highlighting administrative decisions, municipal efforts (committees and public consultations) and publications that shaped or have attempted to shape the current regulations and their enforcement in an effort to modernize them.

## Siting And Planning For The Ground Run-Up Enclosure (Gre) At Billy Bishop Airport

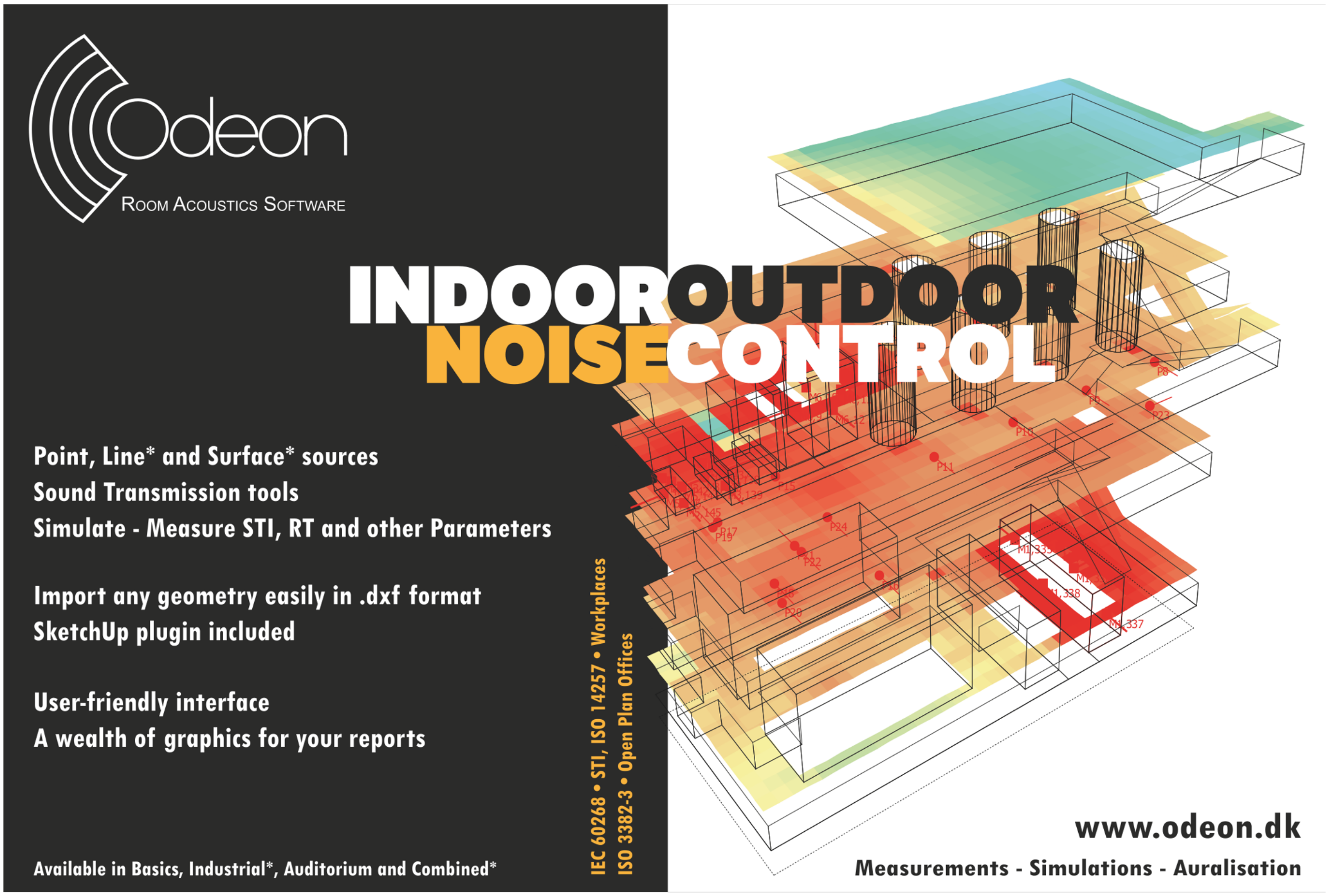
*Nicholas Sylvestre-Williams*

There are requirements that after aircraft maintenance has been completed, engines are required to be tested at take-off power to ensure the proper operation of the aircraft. These activities can be as short as five (5) minutes but can last much longer, and are generally known as a Ground Run-Up in the aviation industry. At an engine's full power, the noise generated can be significant, and for an airport in proximity to neighbouring communities, the noise has the potential to disturb. To address this concern, Billy Bishop Toronto City Airport (BBTCA) operator, Ports Toronto retained Aercoustics to assist in the siting and impact of a Ground Run-up Enclosure (GRE). A Ground Run-Up Enclosure is a specially designed enclosure for the aircraft to conduct ground run-ups while minimizing noise to neighbouring to sensitive areas. This paper will discuss the process in determining the location of the GRE and the modelling of the impacts, with final results of the construction and post-construction measurements.

## A Vital Role In Resolving Rail Related Noise And Vibration Complaints

*Jason Tsang*

Since June of 2007, the Canadian Transportation Agency (Agency) has played a vital role in resolving rail complaints related to railway construction and operation. In resolving rail related complaints, the Agency offers facilitation, mediation, or adjudication services based on its authority established in the Canada Transportation Act. When adjudicating complaints, the Agency looks at three factors: a railway company's level of service obligations, its operational requirements, and the area where the rail activity takes place. This important work touches communities across Canada and is pivotal in the implementation of the National Transportation Policy.



# HEARING SCIENCES - SCIENCES DE L'AUDITION

# GENERATING INVERSE FILTERS FOR HpTF EQUALIZATION AS PART OF HEADPHONE PLAYBACK OF BINAURAL AUDIO

**Ryan Bessey** *[1]
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## 1 Introduction

To generate realistic 3D sound via playback of binaural audio over headphones, the pressure input to the eardrum should match that experienced in the actual sound field. For practical reasons, binaural recordings are not typically made at the eardrum. It is easier and safer to perform binaural recordings at the entrance to a blocked ear canal. However, correction is then required for the acoustical changes created by a blocked ear canal, the effect of headphones occluding the ear, and the fact that sound propagation from the headphone to the eardrum significantly alters the eardrum pressure. These effects can be combined and used to generate an equalization filter that will result in the required ear drum pressure. While the frequency response of the filter is important, for implementation in the time domain as a convolution, the impulse response should not introduce temporal artifacts.

## 2 Method

Rather than compensate for the influence acoustical changes impart by the headphone, many researchers have relied on Free-Air Equivalent Coupling (FEC) headphones [1]. However, even open-headphones only fulfill this condition at lower frequencies.

Based on estimates of the listener's ear canal effective length and area, as well as published models for the eardrum impedance [2], the ear canal input impedance was calculated using an acoustical transmission line. The ear canal radiation impedance was determined using the baffled piston formula. For the headphone output impedance, reliance was made on published data for similar headphones [3]. Using these inputs with an equivalent circuit analysis, it was possible to determine the Pressure Division Ratio (PDR), which compensates for the effect of a block ear canal as per equation 1.

The Frequency Response Function of the headphone ($FRF_{b,hp}$) was measured at the blocked ear canal entrance using the same microphones as for the binaural recording, which causes the microphone response to cancel as part of the equalization process. An inverse Headphone Transfer Function (HpTF) filter deemed G was then generated based on equation 2.

$$PDR = \frac{Z_{in} + Z_{hp}}{Z_{in} + Z_{rad}} \quad (1) \qquad G = \frac{1}{HpTF} = \frac{PDR}{FRF_{b,hp}} \quad (2)$$

Since direct inversion of the HpTF was found to cause temporal artifacts which, depending on the HpTF, could be unstable, a Band Pass Filter (BPF) from 20 Hz to 20,000 was included as part of the inverse, and regularization was performed using an effort term (B) weighted towards frequencies above 9000 Hz [4]. The BPF introduced a time delay, which eliminated the temporal issues by shifting the impulse response. Regularization limited the high-frequency effort of the filter for correction of large dips in the estimated HpTF; this helps to ensure a stable inverse. Regularization also decreased post-ring in the impulse response at the expense of slightly more pre-ringing and reduced the potential for equalization error of large peaks that could shift due to headphone re-positioning. The inverse filter with regularization was determined based on equation 3.

$$G_r = \frac{BPF}{HpTF + B} \quad (3)$$

To test the audio quality of the inverse filter, a binaural recording of pink noise played back through separate channels of a 7.1 home theatre system was made. Externalization and localization accuracy was evaluated while seated within the home theatre by A/B comparison between a normalized version of the original recording and one processed with the inverse filter. The two recordings were also compared directly to the sound coming from the loudspeakers.

To evaluate the temporal characteristics, a binaural recording of urban sounds was made and processed with the inverse filter. During listening it was possible to switch between the normalized original recording and the version processed with the inverse filter without interrupting playback. Specific sound events within the recording were looped to allow for any temporal changes to be heard.

## 3 Results

The inverse filters were generated using estimates of the ear canal length and area, inspection of the filter response, and listening tests. However, it is also be possible to indirectly measure the length and area using acoustical techniques [5], [6], potentially with a more accurate result.

The inverse filter magnitude response (with and without regularization) is included below as Figure 1. The effect of regularization can clearly be seen above 9000 Hz. The effort term was adjusted to limit the equalization to approximately 10 dB at high-frequencies, while minimizing the creation of the peak-doublets that can be seen to occur when large narrow peaks are attenuated by regularization.

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The estimated effect of both inverse filters on the eardrum sound pressure were determined using an equivalent circuit model of the ear with a transmission line for the ear canal. The results are illustrated in Figure 2, whereby a full correction can be seen without regularization and reduced high-frequency correction can be seen with regularization.

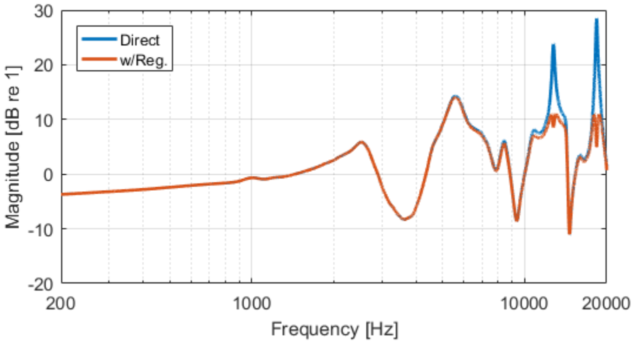

**Figure 1:** Inverse filter magnitude response

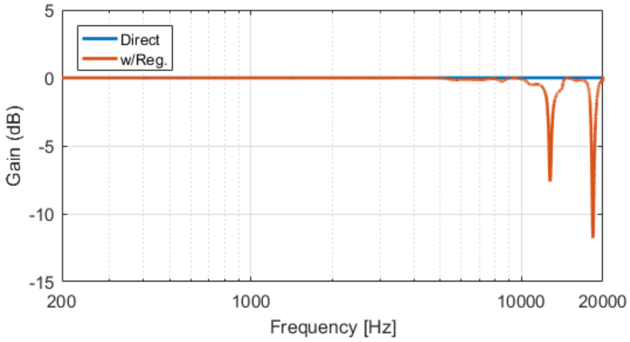

**Figure 2:** Equalized eardrum response

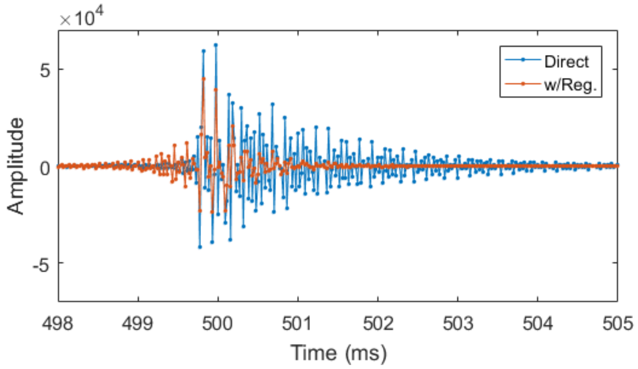

**Figure 3:** Inverse filter impulse response

Zoomed plots of the resulting impulse responses for both inverse filters delayed by the BPF to the centre of a 1 second impulse window are shown in Figure 3. The version with regularization can be seen to have significantly less post-ringing but some additional pre-ringing.

During the headphone listening test of the home theatre system, it was observed that without HpTF equalization, all channels except the centre externalized and appeared to be coming from the loudspeakers. For the center channel, the sound did not externalize and seemed to be located inside the listener's head. This result from the centre channel was expected since frontal localization is known to be particularly challenging, relying mostly on spectral differences between the ears since level and time cues are not present [2].

When listening with equalization of the HpTF, there was a noticeable improvement in the accuracy of the sound image for all channels. This indicates the equalization filter did not negatively affect the fundamental binaural cues. Even for the centre channel, with inverse HpTF equalization the sound image externalized and pulled forward out of the head; however, the image did not pull all the way to the loudspeaker and seemed to be coming from a point in space in front of the listener. This suggests that the estimated HpTF must be close to the actual HpTF but not an exact match.

For all loudspeaker locations, with inverse HpTF equalization, a noticeable change in high-frequency timbre was heard. This likely occurred due to a mismatch between the estimated HpTF and the actual HpTF of the listener. This mismatch prevents the brain from fully correcting the observed timbre.

When listening to the urban-sound recordings without HpTF equalization, the sound was realistic and did externalize, but seemed to be lacking high-frequency energy. With HpTF equalization, the overall sound quality was improved due to the high-frequency boost and sound sources seemed to originate from a more precise location in space. In terms of phase and temporal effects, there was no audible difference indicating that both the pre-ringing and filter decay of the inverse filter were adequately damped.

## 4 Conclusion

A method of estimating an HpTF equalization filter applicable to blocked ear canal binaural recordings was developed and tested. Listening test results demonstrated that the filter can improve externalization, localization accuracy, and overall audio quality. With improved means of estimating the required input parameters, it is expected that the technique could be used as part of binaural audio reproduction system.

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# LOUDNESS IN THE OCCLUDED EAR CANAL: ARE WE AGAIN MISSING 6 dB?

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## 1 Introduction

Over the last century, Auditory Research has been repeatedly reporting differences between earphone/earbud and free-field loudness perception. Although it is still unclear today what causes these differences, many possible explanations have been given; one of them being that ear occlusion modifies the subject's perception of loudness. In this paper, we shall try to give the full picture on this issue and identify the factors most likely to explain those discrepancies.

## 2 Origins

To the authors' knowledge, the so called "missing 6-dB" problem started with a paper from Sivian & White [1] stating that pressure thresholds observed at low frequencies using conventional earphones mounted in flat cushions were approximately 6 dB higher than thresholds measured on the same subjects when a loudspeaker was the sound source and the subject's ears were uncovered. There was no acceptable explanation given as to why the minimum audible pressure (MAP) differed significantly from the minimum audible field (MAF). This was later confirmed by Munson & Wiener [2] who found that for loudness balancing the reported differences still existed. The fact that those differences were about the same for threshold and supra-threshold levels made it quite tempting to think there could be a generalized explanation for both situations. However, as stated by Rudmose [3], it is quite likely that "there are truly two problems, each with its own solutions". This is something anyone should keep in mind when comparing loudness data, as specific precautions should be taken for each of the scenarios.

## 3 The "end"

Regarding noise levels at threshold, Killion [4] came to the conclusion that the 6 dB difference at minimum audible pressure (MAP) between a loudspeaker and an earphone could be attributed to four methodological shortcomings: i) inadequate determination of actual stimulus levels; ii) physiological noise; iii) transducer distortion, and iv) mechanical vibration coupled to the subject. This was later confirmed through direct measurements by Rudmose [3], who identified masking from physiological noise as the main reason to explain threshold differences at low frequencies for noise generated by earphones mounted in flat cushions.

As for loudness balance tests, Rudmose found a very specific list of factors that may provoke those differences. He also added that if the procedures used in his experiments were followed there should be no missing 6 dB. Those factors are: i) mechanical coupling of the subject's chair (the subject's chair needs to be isolated from the floor); ii) source location; iii) transducer distortion; iv) the formal procedure for performing the balancing, and v) the monaural case problem (for monaural measurements, it must be ensured that the non-tested ear is sufficiently occluded when performing the tests in free-field to avoid comparing monaural data with binaural data). One essential factor is in fact the source location problem. According to Rudmose, "when performing loudness balances between sounds generated by a loudspeaker located across the room with that generated by a loudspeaker near the ear (ear or ears open), some subjects require more sound pressure from the near source than from the distant source for equal loudness". This phenomenon can be explained by the so-called "acoustic size". In other words, some listeners perceive a more distant source as having a "larger acoustic size" and consequently, the smaller source (e.g. earphones) must be "stronger" to equal the loudness of the larger source. From Rudmose's data, this effect is subject dependent and can reach up to 4 dB in the case of supra-aural headphones compared to free-field stimulation. Also, once a subject becomes aware of this phenomenon, he can be trained to eliminate it.

Lastly, Völk & Fastl [5] used binaural synthesis to show that "the same sound-pressure time-functions in the auditory canals ensure the same loudness in loudspeaker and headphone reproduction" and possibly gave a final end to this issue. Their explanation is that "the same loudness perception (and the overall auditory impression) can only be elicited if the auditory event position is comparable in both cases", which confirms the observations made by Rudmose about the importance of source location.

Having said that, one could easily consider "the case of the missing 6 dB" closed. And yet the debate was re-opened as scientists started to question the effects of listening with an obstructed ear canal.

## 4 Return of the jedi

Keidser *et al.* [6] studied the "relative perception of low and high frequency sounds in the open and occluded ear". Their findings revealed that for balancing tests "normal-hearing listeners tend to select an average 10 dB higher level for low-frequency sounds at 500 Hz when listening with the ear occluded than when listening with the ear open". It should

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be noted that the “open ear” was excited by a loudspeaker while sound in the “occluded ear” was delivered by hearing aid receivers. Hence, it is difficult to determine whether ear occlusion actually had an impact on the reported differences as the “acoustic size” parameter may also have influenced the results.

Recently, the present authors undertook a loudness balance experiment [7] where circum-aural headphones were used to present sounds diotically in the open (meaning “no earplug”) and occluded (by an earplug) ear. The results suggested the occluded ear needs more sound power for the same achieved loudness, but further investigations showed that these data may have been impacted by some inter-aural time difference (ITD) introduced by the earplug. Additional tests shall be performed shortly and new results should be presented at the conference.

Using a totally different experiment, Theis *et al*. [8] found that in-ear dosimetry tends to overestimate the noise dose when performed in the occluded ear. Their protocol is based on the assumption that TTS (Temporary Threshold Shift) is a good indicator of the noise dose received by the auditory system. These interesting results should, however, be considered with caution as very few details about the experimental procedure were provided.

## 5 Discussion

Three main changing parameters were identified to describe the large amount of data represented by the above-cited studies: nature of the source (loudspeaker, headphones, in-ear monitors), characteristics of the sound stimuli (spectral and temporal features, excitation level), and the mechanical load applied to the external ear (ear covered with earcups, occluded ear, fully open ear). The discrepancies referred as the original “missing 6 dB problem”, that is when comparing the loudness obtained with a loudspeaker to that with circum- or supra-aural headphones, are regarded by the authors as a solved issue as they have now received several valuable and experiment based explanations [3]–[5]. On the other hand, the differences observed when studying the impact of ear canal occlusion on loudness perception have not been explained, but a few possible explanations are proposed below.

One explanation is that ear occlusion can change the relationship between sound pressure level at the eardrum and the acoustic power entering the middle ear. Various modeling strategies were exercised by the present authors but none seems to be able to support such theory, unless it is provoked by some modification of middle ear impedance when the ear canal is occluded. Moreover, if this effect were to exist, one would expect it to occur at threshold levels as well as supra-threshold levels. Yet, the fact that threshold detection occurs at a constant eardrum pressure has been generally accepted in the scientific community [4] and no differences have been reported at threshold levels despite the use of both in-ear and supra-aural earphones for audiometric testing. Besides, a change of middle ear impedance is unlikely to be the answer as neither the acoustic reflex or added static pressure could explain our latest results [7].

Another possibility is that the factors causing the discrepancies observed for the occluded ear canal are the same involved in the original “missing 6 dB problem”, although the data from Theis *et al*. [8] remain unexplained by such considerations. Regarding the results from Keidser *et al*. [6], the source location could easily have affected the results. The amplitude of the effect (10 dB instead of 4 dB as mentioned by Rudmose [3]) could be due to the increased source proximity inherent to the use of in-ear receivers. As for the recent findings from Bonnet *et al*. [7], it is known that earplugs can affect our ability to localize sounds [9]. Therefore, the earplug might affect the lateralization task even once the ITD issue is solved in future experiments.

## 6 Conclusions

Based on our own experimental measurements and those from other inquisitive studies, focus was made on the factors that should be considered when studying the effect of ear canal occlusion on loudness perception and/or risks of hearing damage. A list of studies was provided, but we believe additional data are needed to draw more specific conclusions on this issue. Hopefully, upcoming tests will help resolve the problem.

## Acknowledgments

The IRSST (Quebec occupational health and safety research institute) is gratefully acknowledged for their financial support.

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# OBJECTIVE ASSESSMENT OF COMPANDING ARCHITECTURE FOR ASSISTIVE HEARING DEVICES

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## 1 Introduction

Understanding speech in noisy environments is a significant challenge for hearing impaired listeners. The situation becomes more challenging with poorer Signal-to-Noise Ratios (SNRs). The listening difficulty arises from deficits in temporal, spectral, binaural, and/or cognitive processing. This research focuses on enhancing speech for hearing impaired listeners with poor temporal and spectral processing (e.g., individuals with auditory neuropathy spectrum disorder (ANSD) [1] . In particular, the present research evaluates the performance of a companding signal processing architecture in enhancing both temporal and spectral cues within a speech signal. Previous research has shown that this companding architecture enhances speech perception by ANSD and Cochlear Implant (CI) subjects [1,4], and the present work builds on the earlier published results.

In order to evaluate the performance of the companding architecture, subjective and/or objective quality and intelligibility measurements are required. Subjective methods require individuals to judge the quality and intelligibility of the processed speech signal. However, subjective measurements are costly and time consuming processes [2]. As a result, computer-based objective measurement techniques have been proposed to estimate speech intelligibility and quality in the presence or absence of background noise. Generally, objective measurement methods can be divided into two categories: intrusive or non-intrusive [2]. The intrusive techniques perform the measurement with respect to a reference signal (clean speech), whereas the non-intrusive methods perform the measurement independent of the reference speech signal. In the present study, the performance of the companding architecture was assessed objectively using a non-intrusive metric, the speech-to-reverberation modulation energy ratio (SRMR). The objective assessment was conducted across two experiments. In the first experiment, the noisy speech stimuli at different SNRs were processed with the companding architecture, and the processed stimuli were assessed using the objective metric. The second experiment was similar to first, except a Minimum-Mean-Square-Error (MMSE) noise reduction algorithm [3] was applied before processing through the companding architecture. Results from these experiments are expected to signify the practical application of companding architecture in assistive hearing devices.

The remainder of this paper is organized as follows: Section 2 presents a brief overview of the companding architecture, the noise reduction algorithm, and the SRMR metric. Section 3 reports the experimental methodology and results, and section 4 concludes the paper.

## 2 Companding, noise reduction, and SRMR

### 2.1 Companding architecture

The companding algorithm for the present study was adopted from Bhattacharya & Zeng [4] and implemented in MATLAB. Fig. 1 illustrates the block diagram for a single channel in the companding architecture. The algorithm consists of two individual blocks: compression and expansion. The input speech signal is first divided into 50 frequency channels using a bank of relatively broad band bandpass filters (BBBPFs). Next, the signal in each channel is subjected to amplitude compression. The compression index ($n_1$) and the output of the envelope detector (ED) determine the amount of compression. The compressed speech signal is then passed through a relatively narrow bandpass filters (NBBPFs) before being expanded in the expansion block. The amount of expansion is determined by the corresponding ED output and the ratio $(n_2-n_1)/n_1$, where $n_2$ is the expansion index. Subsequently, the outputs from all the channels are combined to obtain the processed signal.

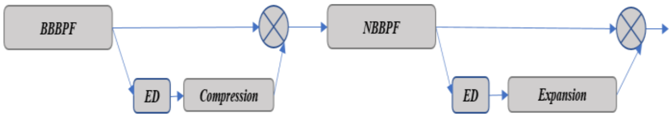

**Figure 1:** A single channel within the companding architecture [4].

### 2.2 Noise reduction algorithm

In a typical hearing aid application, the acoustic mixture of speech and background noise is received by the hearing aid microphones. However, it is known that the effectiveness of the companding algorithm reduces in the presence of background noise [1]. Hence, a noise reduction algorithm is imperative as a front-end to the companding algorithm. In the present research study, the MMSE noise reduction algorithm [3] was applied to noisy speech at different SNR conditions before applying the companding algorithm. The MMSE algorithm was chosen as it generates fewer artifacts (“musical noise”) typically associated with noise reduction algorithms [3].

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### 2.3 SRMR objective measurement

Computation of the SRMR metric involves the following steps [2]. First, cochlear processing is emulated by passing the input signal through a 23-channel gammatone filterbank. Second, temporal envelopes are extracted in each channel using the Hilbert transform and multiplied by the Hamming window. Third, the modulation spectral energy in each channel is computed as the squared magnitude of the discrete Fourier transform of the temporal envelope. Finally, the modulation energy across all acoustic frequencies is computed for lower and higher modulation frequency bands, and the ratio of modulation energy in lower/higher modulation frequency bands is the SRMR metric [2].

## 3 Experimental methodology and results

### 3.1 Method

The companding algorithm was implemented in MATLAB, with the $n_1$ and $n_2$ parameters set to 0.3 and 1 respectively for all the experiments. In addition, the Root-Mean-Square (RMS) value of the companded signal was equated to that of the original input signal.

The clean speech sentences used in the present study were taken from the hearing in noise test (HINT) database [5]. This test contains 25 lists with each list consisting of 10 sentences which are phonetically balanced, and are equally difficult. It is pertinent to point that one list is selected randomly for each condition and/or experiments described below. Objective results are shown as the SRMR scores, averaged over the ten sentences in that randomly selected list. In conditions involving background noise, the HINT speech-shaped-noise was mixed with the clean speech at different SNRs before applying the noise reduction and/or companding algorithms.

### 3.2 Results

Fig. 2 displays a sample experimental result wherein the long-term averaged spectra of noisy speech (SNR = 0 dB) are compared across three processing conditions: unprocessed, companding alone, and a combination of noise reduction and companding. It can be seen that companding alone does sharpen the speech spectral peaks. However, applying both noise reduction and companding to noisy speech at the same SNR value results in a significantly better sharpening of the spectral peaks.

In addition, Fig. 3 depicts the SRMR metric computed across different SNR and processing conditions. Note that a higher SRMR value denotes a more intelligible signal. The results from Fig. 3 demonstrate a significant benefit of the companding condition over unprocessed, regardless of the SNR value. Furthermore, results from Fig 3 reveal that the application of noise reduction algorithm can improve the performance of companding architecture, once again irrespective of the SNR value. It can also be seen that the amount of improvement with the noise reduction algorithm was significantly higher for SNRs less than 15 dB.

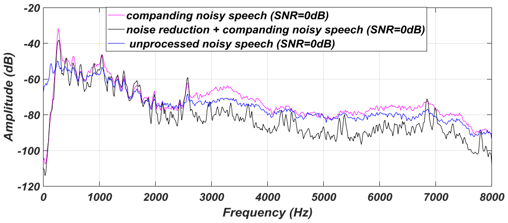

**Figure 2:** Comparison of long-term average power spectra

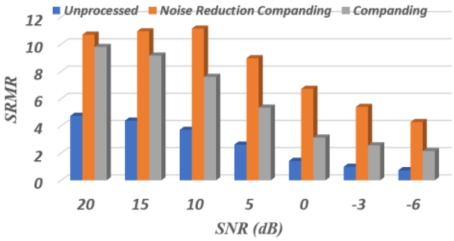

**Figure 3:** SRMR values for different processing conditions

## 4 Conclusion

Two experiments were conducted to investigate the performance of a companding architecture objectively using the SRMR metric. The first experiment was conducted to explore the performance of the companding algorithm in terms of the predicted speech intelligibility score in the presence of background noise. The second experiment was conducted to evaluate the effectiveness of the same companding architecture by incorporating an additional noise reduction algorithm. Results showed that the incorporation of the noise reduction algorithm does expand the effectiveness of the companding algorithm over a wider SNR range. These results can potentially guide the choice and activation of companding architecture in assistive hearing devices.

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# UPPER LIMITS OF AUDITORY MOTION PERCEPTION WITH PERCUSSION SOUNDS

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## 1 Introduction

Since the 16th century, composers have used spatialization in their compositions. Iannis Xenakis, for instance, wrote *Persephassa* for six percussionists, with up to six streams of instruments, rotating clockwise and counterclockwise around the audience [1]. And with technological progress and the emergence of electroacoustic music, composers are increasingly interested in moving sounds in space.

Yet, little is known about human auditory perception of rotation. Féron, Frissen, Boissinot, and Guastavino [2] have measured the upper limit of auditory motion perception; that is, the highest velocity beyond which participants can not perceive if sounds are rotating around them. They found that the average upper limits were up to 2.8 rot/s. Moreover, the upper limited decreased as the stimuli contained increasingly less low-frequency content, suggesting a particular importance for interaural time differences in tracking auditory motion.

The little work available is based on the use of synthetic sounds and manipulations in the spectral domain. This study is the first to investigate upper limits with recordings of percussive sounds which contain both spectral and temporal complexity.

## 2 Experiment 1

### 2.1 Method

**Participants**

Twenty-one participants (11 women) with reported normal hearing, of average age 25.4 years (SD = 4.3), and musically trained (minimum: 1 year; average: M = 11.9 years, SD = 6.2), were recruited via emails sent to the school of music at McGill University and the CIRMMT news list.

**Setup and stimuli**

The experimental setup was reproduced from Féron et al. [2]. It consisted of a horizontal circular array of 16 speakers with a diameter of 3.7 m centered on the participant's head. The rendering system takes into account motion-dependent propagation and reflections [3].

The stimuli were obtained from isolated recordings of each of the six players in *Persephassa* [4]. We created brief (0.6 to 3.7 s), clean, and looping excerpts of two instruments from each family of percussions (skin, metal, wood) used in the piece. We also added a condition with pink noise to serve as a control and to allow comparison with previous studies. All stimuli were normalized in amplitude to -20 dB (in RMS or peak levels) and then equalized in loudness.

**Procedure**

We had seven conditions, tested separately in seven sessions presented in randomized order: one high tom, one snare drum, one cymbal, one metallic *simantra*, two wooden *simantras*, and a pink noise. The first *Simantra* was played in a sort of slow single stroke four way and the second *Simantra* was played faster, like a stroke roll.

Upper limits were estimated with a two-alternative forced choice 2-up, 1-down staircase procedure, with a starting velocity of 1.3 rot/s. The task was to indicate the direction of rotation (clockwise or counter-clockwise) of the sound stimulus. A total of four staircases, two in each direction, were intertwined in each session to make sure the participants did not realize the type of procedure being used. Each staircase stopped after either 12 reversals or 60 trials, whichever came first.

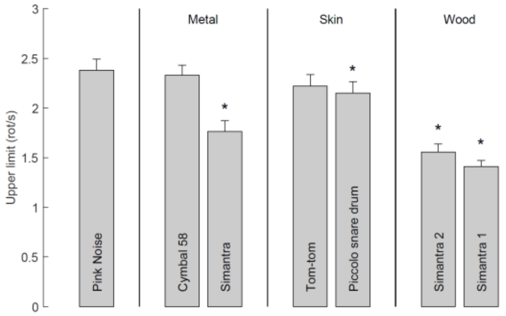

**Figure 1:** Upper limits for each condition of experiment 1 (N = 21). The asterisks denote a significant difference compared to the pink noise (p < .01)

**Analyses**

The analyses were conducted in MATLAB® (R2015b). For each staircase, the mean of the last four reversals was calculated. And for each condition, the means of the four staircases were averaged.

### 2.2 Results and discussion

The main results are shown in Figure 1. The upper limits for the three simantras (metal: t(20)=7.14, p < .001; wood 1: t(20)=8.12, p < .001; wood 2: t(20)=9.95, p < .001) and the piccolo snare drum (t(20)=3.62, p < .01) are significantly lower than for pink noise. The upper limits for the two metal

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instruments (simantra and cymbal) are also significantly (t(20)=5.89, p < .001) different from each other.

The upper limit for the pink noise was 2.4 rot/s, similar to the one for white noise from Féron et al. [2]. Among the set of stimuli, the upper limits for the three simantras are markedly lower. This reduction could be a due to differences in the temporal and spectral domain. That is, acoustic analysis revealed that the Simantra stimuli had a relatively lower event density and were less noise-like.

# 3 Experiment 2

## 3.1 Method

To explore the contribution of event density, and the noise-like quality of the signal, we conducted additional testing with the wooden *Simantra 1*, which is the condition with the lowest upper limit, and the most clearly discrete strokes. Specifically, we manipulated event density by controlling the beat frequency and we manipulated the noise-like character of the stimulus by superimposing levels of pink noise. After a small pilot to determine the signal-to-noise ratios (SNR) to use, we reproduced the same procedure.

### Participants

Ten new participants (4 women) with reported normal hearing, of average age 27.0 years (SD = 5.9), and with sound-related knowledge and/or musical training (min.: 6 months; average: M = 10.1 years, SD = 7.6) were recruited from the same populations.

### Stimuli

New stimuli were created by doubling the beat frequency and adding pink noise (in Audacity®) to the condition *Simantra 1* from the previous experiment.

We had seven conditions: the same pink noise as in experiment 1, as well as the same *Simantra 1* with no noise, 0.02, or 0.1 of added noise, and the same three *simantra* conditions with the beat density doubled. Table 1 lists the stimuli's signal-to-noise ratios.

**Table 1:** Signal-to-noise ratios (SNR) for the new conditions

| | | Beat frequency | |
|---|---|---|---|
| | | x1 | x2 |
| SNR | 0.02 | +0.2 dB | -2.0 dB |
| | 0.1 | -0.7 dB | -2.6 dB |

## 3.2 Results and discussion

The upper limits for the two no-noise conditions are significantly lower than those for the pink noise (original: t(9)=8.93, p < .001; doubled beat: t(9)=7.04, p < .001), and the added-noise conditions (original 0.02: t(9)=5.34, p < .001; original 0.1: t(9)=6.77, p < .001; double beat 0.02: t(9)=6.95, p < .001; double beat 0.1: t(9)=9.61, p < .001; Figure 2). The upper limits between noise conditions are similar within the groups of same beat frequency. The upper limits for each of the two no-noise conditions are significantly different (t(9)=3.10, p < .05).

An additional repeated measures ANOVA, with beat frequency and SNR as factors, shows a main effect of beat frequency (F(1, 9) = 29.845, p < .001) and SNR (F(2, 18) = 99.573, p < .001), with no interaction. The pairwise comparisons for SNR confirm that the upper limits for the no-noise stimuli are significantly lower than for the added-noise stimuli (p < .001).

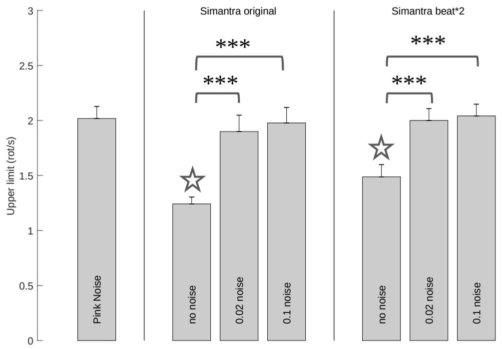

**Figure 2:** Upper limits for each condition of experiment 2 (N = 10). The stars denote a significant (p < .001) difference compared to the pink noise. ***, p < .001.

The upper limit improves sharply with the addition of noise, and mildly with the increase in beat frequency. This indicates that both spectral and temporal factors contribute to the upper limit, though in different proportions.

# 4 Conclusion

This was the first study to explore the influence of temporal and spectral complexity on the auditory perception of rotation. Overall, the upper limits we have estimated for real musical sounds are similar to the upper limits previously estimated for synthetic sounds. However, we need to disentangle the effects of temporal and spectral content. A further step will look into it with stimuli blending noise and percussive sounds, with the same temporal envelope.

# Acknowledgments

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# EARTRODES: TOWARDS A WIRELESS IN-EAR CUSTOM-FITTED BRAIN COMPUTER INTERFACE

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## 1 Introduction and objectives

Brain-computer interfaces (BCI) can directly translate human intentions into discrete commands, bypassing the motor system. Most non-invasive BCI systems currently in use are based on electroencephalography (EEG) recording technology, thanks to recent developments toward mobile EEG solutions. However these systems are currently facing important limitations. In addition to be robust to motions, sensors of mobile EEG-based BCI systems should also be as inconspicuous as possible to be adequate for social settings. The present study evaluates the signal quality of auditory steady state responses (ASSRs) obtained with an unobtrusive earpiece, dubbed "EARtrodes", incorporating in- and around-the-ear electrodes and compared to those obtained with well-established gold-plated electrodes.

## 2 Material and method

### 2.1 Overview the ASSRs

ASSRs are electrophysiological responses, recorded from the human scalp, and often evoked by one or more carrier frequencies (Fc) that are amplitude-modulated at a specific frequency (Fm). In practice, when a subject is exposed to such a stimulus, spectral power of the EEG frequency spectrum of the subject that is related to the stimulus will be manifest at Fm, and may also appear at its harmonics [1]. ASSR recordings and stimuli generations were conducted by using the LabVIEW™ based "MASTER SYSTEM™" Rotman Research software.

### 2.2 Overview of the MASTER SYSTEM

The MASTER SYSTEM is a data acquisition system designed by Michael S. John & Terrence W. Picton [2] to assess human hearing by recording auditory steady-state responses. This LabVIEW based environment simultaneously generates multiple amplitude-modulated and/or frequency-modulated auditory stimuli, acquires electrophysiological responses to these stimuli, displays these responses in the frequency-domain, and determines whether or not the responses are significantly larger than background physiological activity. Typical hardware of the MASTER SYSTEM (Fig. 1) includes a PC, an acquisition board, a variable gain amplifier, an audiometer, a transducer (usually, earphones or headphones), an EEG amplifier, BNC and audio cables, and a set of gold-plated electrodes placed at vertex (Cz), on the back of the neck (reference) and on the clavicle (ground).

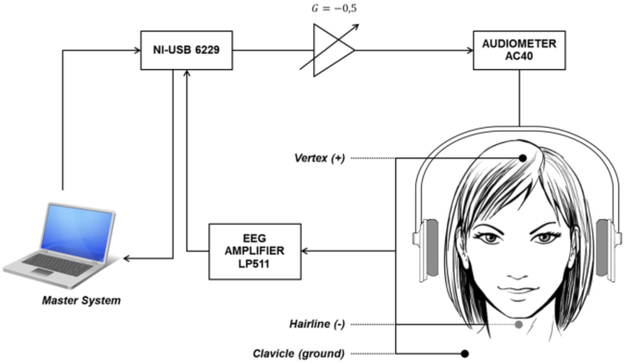

**Figure 1:** Overview of the MASTER system. All components are monitored by a single PC. The stimulation signals from the analogue output of the NI-USB 6229 board are attenuated by an operational amplifier with a gain of -0.5, so that they may be delivered to the "tape input" of the audiometer, which enables the operator to adjust the levels of stimuli delivered by the transducer. In parallel, ASSRs are scalp-recorded on the electrodes (placed between vertex (+) and hairline (ref), with clavicle as a ground) and are then amplified by an EEG amplifier, before reaching the analogue input of the data acquisition board. Data is processed online through the LabVIEW based software.

### 2.3 Overview of the EARtrodes

The EARtrodes (Fig. 2) consist of a custom-fitted earpiece which incorporates a custom-fitted earplug coupled with a behind-the-ear piece forming a 7 miniaturized wet electrodes interface. The shape of the behind-the-ear piece was designed by the authors with the help of outer ear impressions made on ten subjects in order to optimize a good contact quality.

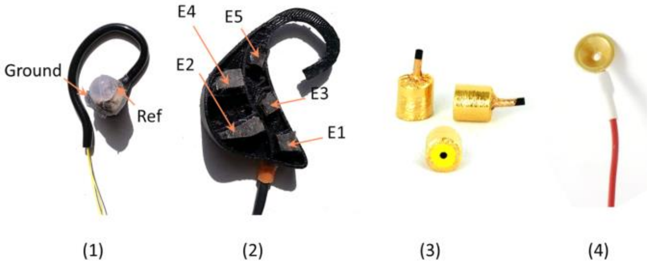

**Figure 2:** Electrodes used for this study: EARtrodes' custom-fitted earplug (1) and behind-the ear piece (2), gold foil electrodes (3) and gold-plated cup electrodes (4).

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Additive manufacturing and casting techniques has been used to build the custom-fitted earplug with electrodes. All electrodes were made of silicone filled with carbon chopper.

### 2.4 Participants

Five men with ages from 19 to 29 and hearing thresholds below 20 dB HL (from 125 Hz to 8 kHz) were assessed. The study was reviewed and approved by the “Comité d’éthique de la recherche”, the internal review board (IRB) of the École de technologie supérieure.

### 2.5 Experimental procedure

A typical experiment procedure included two recording sessions whose purpose was to compare ASSRs scalp-recorded with the EARtrodes’ behind-the-ear piece and custom-fitted earpiece to those obtain with gold foil or gold-plated cup electrodes. For both experiment, the stimuli consisted of four pure tones (500, 1000, 2000 and 4000 Hz) amplitude modulated at 40 Hz with a depth of 100 %. The different placements used for each experiment are reported in Table 1.

## 3 Results and discussion

Although EARtrodes' signals show lower amplitudes, corresponding signal-to-noise ratios of ASSRs recorded with EARtrodes were similar to those of ASSRs recorded with gold electrodes (Fig. 3 and 4). As a consequence, the proposed EARtrodes seems to be a promising candidate for future small, mobile, and unobtrusive BCI platforms. Further research is still needed to investigate event-related potentials, such as the one obtained from an auditory oddball or a mismatch negativity paradigm, to further validate the proposed system. In the long term ear-EEG systems like EARtrodes could be merged with other audio devices, such as hearing aids and headphones, to build next-generation devices that dynamically adapt to the listener’s intentions and cognitive state changes.

## Acknowledgments

The authors wish to acknowledge the financial support received from the NSERC-EERS Industrial Research Chair in In-Ear Technologies (CRITIAS), MITACS and EERS 4.0 Inc. (Montréal, Québec, Canada). The first author also thanks CIRMMT travel fund scholarship for supporting the presentation of these results.

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**Table 1:** Electrodes’ placements used for the two experiments. «G.P.C» refers to gold-plated cup electrodes, «G.F» refers to gold-foil electrodes and «EAR» refers to EARtrodes’ electrodes.

| | | **Reference** | **Ground** | **+** |
|---|---|---|---|---|
| **Exp. #1** | Control condition #1 | Hairline (G.P.C) | Clavicle (G.P) | Vertex (G.P.C) |
| | Control condition #2 | Wet In-ear (G.F) | | |
| | Measurements #1 to #5 | | | Around-the-ear (EAR) |
| **Exp. #2** | Control condition #1 | Hairline (G.P.C) | Clavicle (G.P.C) | Vertex (G.P.C) |
| | Control condition #2 | Wet In-ear (G.F) | | |
| | Measurements #1 | Dry In-ear (EAR) | | |
| | Measurements #2 | Wet In-ear (EAR) | | |
| | Measurements #3 | Wet In-ear (EAR) | Wet In-ear (EAR) | |

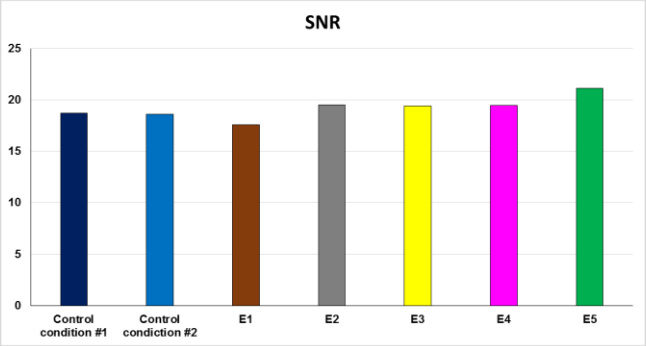

**Figure 3:** Signal-to-noise ratio, in dB, of ASSRs scalp-recorded on subject #1 using gold electrodes (control condition #1 and #2) and EARtrodes’ behind-the-ear piece (E1 to E5). Electrodes placements are detailed in Table 1.

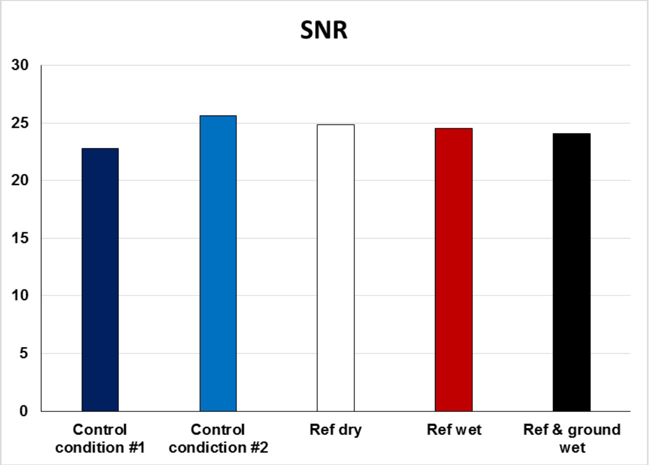

**Figure 4:** Signal-to-noise ratio, in dB, of ASSRs scalp-recorded on subject #3 using gold electrodes (control condition #1 and #2) and EARtrodes’ custom-fitted earpiece.

# ABSTRACTS FOR PRESENTATIONS WITHOUT PROCEEDINGS PAPER
# RÉSUMÉS DES COMMUNICATIONS SANS ARTICLE

## Effects Of Short-Term Choir Participation On Auditory Perception In Older Adults.

*Ella Dubinsky, Gabriel Nespoli, Frank Russo*

Hearing loss, which most adults will experience to some degree as they age, has been associated with decreased emotional wellbeing and reduced quality of life in aging adults. Although assistive technologies (e.g., hearing aids) can target aspects of peripheral hearing loss, persistent perceptual deficits are widely reported. One prevalent example is the loss of the ability to perceive speech in a noisy environment, which severely impacts quality of life and goes relatively unremediated by hearing aids. Musicianship has been shown to improve aspects of auditory processing, but has not been studied as a short-term intervention for improving these abilities in older adults. The current study investigates whether short-term choir participation can improve three aspects of auditory processing: perception of speech in noise, pitch discrimination, and the neural response to brief auditory stimuli (frequency following response; FFR). Forty-six older adults (aged 50+) participated in a choir for 10 weeks, during which they took part in group singing (2 hours/week) supported by individual online musical training (1 hour/week). Choir participants (n=46) underwent pre- and post-training assessments, conducted during the first week of the choir and again after the last week. Two control groups were assessed, including a group of older adults (aged 50+) involved in 10 weeks of music appreciation classes (music perception group; n=17), and an age- and audiometry-matched do-nothing control group (aged 50+; n=25). Control participants underwent the same battery of assessments, measured twice over the same time frame as the choir participants. Auditory assessments were administered electronically, and the FFR was obtained using electroencephalography (EEG). Preliminary statistical analyses showed that choir participants improved across all auditory measures, while both control groups showed no differences. These findings support our hypothesis that short-term choir participation is an effective intervention for neural and perceptual aspects of age-related hearing loss.

## Brain Entrain: Acoustic Features Of Music That Drive You To Synch

*Gabriel A Nespoli, Sean Gilmore, Frank A Russo*

Tapping along with a metronome or the beat of music is a relatively easy task. Certain acoustic features of music have been found to support this behavioural synchronization. For example, lower frequency content has been found to be related to higher tapping velocity and lower tapping variability (Stupacher, Hove, &amp; Janata, 2016). Neurons will also entrain their firing to the beat of music, but it is unknown whether those same acoustic features that support behavioural synchronization will also support neural entrainment. The current study seeks to investigate which acoustic features of music support the entrainment of neurons that are related to behavioural synchronization, such as those in premotor areas of the brain. In a previous study, participants listened to music while EEG was measured from the surface of the scalp. Independent components analysis was used to identify sources of activity in auditory and premotor areas of the brain. In a post-hoc analysis, certain acoustic features of the music were found to correlate with neural entrainment. Specifically, tempo and RMS were found to correlate with entrainment of premotor areas, whereas low energy rate (the proportion of the signal below the average energy) and spectral centroid were found to correlate with beta-band phase coherence of auditory and premotor areas. In a second [pilot] study, a stimulus set was created to specifically investigate these features and their ability to entrain neurons in premotor areas of the brain.

## Surveying The Sounds Used In Auditory Perception Research: Journal Of The Acoustical Society Of America

*Michael Schutz, Jess Gillard*

A sound's decay conveys useful information to listeners, such as the materials as well as the force involved in the impact event (Gygi, Kidd, &amp; Watson, 2004). Yet its role is often overlooked in auditory perception experiments employing trapezoidally-shaped "flat" amplitude envelopes. My team has documented that time varying sounds can lead to considerably different understandings of perceptual organization in tasks ranging from audio-visual integration (Schutz, 2009) and duration assessment (Vallet, Shore, &amp; Schutz, 2014) to memory recall (Schutz, Stefanucci, Baum &amp; Roth, 2017). To establish a baseline understanding of the range of sounds used in auditory perception research, we analyzed 215 experiments from 111 articles published the Journal of the Acoustical Society of America (JASA) using methodology similar to my team's previous survey of the journal Music

Perception (Vaisberg &amp; Schutz, 2014). Here we found 78% of auditory perception stimuli exhibited “flat” amplitude envelopes, with clicks/click trains accounting for an additional 7.8%. Only 2.8% exhibited the kinds of complex changes in amplitude found in natural sounds. Although the remaining 11.2% used sounds with some time varying amplitude information, this variation lacked any real-world referent (i.e., amplitude modulated tones, “pyramid shaped” tones with matched rise/fall times, etc.). Therefore less than 3% of the sounds exhibited the kinds of complex changes in amplitude found in (and informative about) natural sounds. Moreover 86% of stimuli used in our survey exhibited no amplitude variation beyond abrupt onsets/offsets. This distribution is broadly consistent with my team’s surveys of other journals, indicating the under-assessment of sounds with complex amplitude variations is wide spread issue within psychological acoustics. I will discuss the implications of this previously undocumented challenge, as well as highlight implications for future research opportunities

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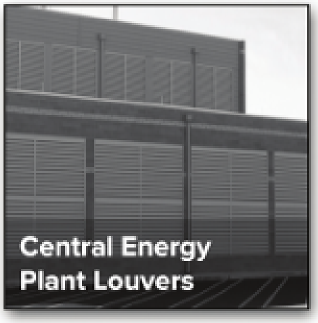

# OCCUPATIONAL NOISE AND STANDARDS - BRUIT EN MILIEU DE TRAVAIL ET NORMALISATION

# INSERTION LOSS OF HEARING PROTECTION DEVICES FOR MILITARY IMPULSE NOISE

**Ann Nakashima [*1], Sadri Sarray [†2] and Nir Fink [†3]**
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[2]Quality Engineering Test Establishment, Department of National Defence, Canada.
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## 1 Introduction

Military operators are exposed to a broad range of complex noises from various types of equipment. In particular, impulse noise from different weapons can vary greatly in terms of level, temporal and spectral characteristics. The American National Standards Institute/Acoustical Society of America (ANSI/ASA) S12.42 describes methods for measuring the impulse peak insertion loss (IPIL) of hearing protection devices (HPDs) [1]. The IPIL is a single number that gives the overall reduction of the peak sound pressure level that is provided by a HPD. However, the measurement methods in the standard are difficult to achieve in practice, and it is unknown if the results can be applied to non-idealized impulse noise sources and realistic operational conditions [1]. In addition, recent studies have shown that the IPIL does not completely describe the performance of HPDs, and that the frequency-domain impulse spectral insertion loss (ISIL) must be considered [2]. In a previous study, IPIL measurements for different types of HPDs for one type of noise source were reported [3]. The current paper presents insertion loss measurements using different HPDs with several different weapons used as noise sources.

## 2 Method

Three types of Canadian Armed Forces (CAF) weapons were used as noise sources for the HPD insertion loss (IL) measurements: a 5.56 mm semi-automatic rifle, a 7.62 mm medium machine gun and a 12.7 mm heavy machine gun. IL data were acquired using a GRAS 45 CB acoustic test fixture (ATF), a 67S blast probe and a Sinus Soundbook data acquisition system with Samurai software (204.8 kHz sampling rate), or a HBM Genesis high-speed transient recorder and data acquisition system (1 MHz sampling rate). Two types of Israel Defense Forces (IDF) weapons were used as noise sources: a grenade launcher and a mortar. Data were acquired using an ATF produced by the French-German Institute of Saint-Louis (ISL) and a Soundbook with Samurai software. The equipment met ANSI/ASA S12.42 requirements for measuring IPIL, but the noise sources were not ideal. Since our objective was to study HPDs for specific weapons, we accepted this limitation and refer to our results as IL and ISIL rather than IPIL. Several types of earplugs and earmuffs were used, alone and in combination. The results shown here will be limited to two passive earplugs and one electronic earmuff: 3M EAR Classic (level-independent passive earplug), Etymotic ETY Plug (linear attenuation passive earplug), 3M Peltor Tactical 6-S (electronic level-dependent earmuff) and the EAR Classic in combination with the Peltor earmuff.

## 3 Results

The pressure-time signals of the CAF rifle and machine guns are shown in Fig. 1. The rifle noise was measured with the blast probe in front of the weapon to reduce reflections. The shockwave seen in Fig. 1 (top) was removed for the analysis. The peak level of the 5.56 mm muzzle blast was 153 dB SPL. The 7.62 mm and 12.7 mm machine gun signals in the middle and bottom of Fig. 1 were measured at the blast probe 0.5 m behind and to the left of the gunner. The peak levels were 154 and 152 dB SPL, respectively.

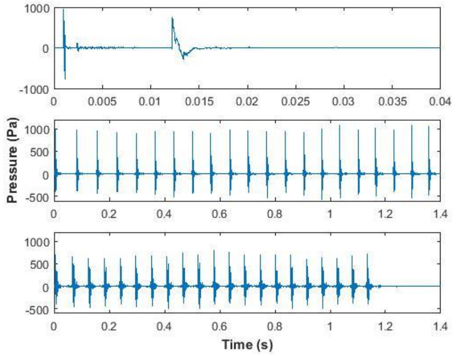

**Figure 1:** Time signal of a 5.56 mm rifle (top) and 21-round bursts from 7.62 mm (middle) and 12.7 mm (bottom) machine guns.

The pressure-time signals of the IDF grenade launcher and mortar, measured in-ear with the ATF, are shown in Fig. 2. The ATF was placed 0.5 m to the right of the gunner for the grenade launcher, and 0.5 m behind the mortar. These signals have been modified by the ear transfer function, but they clearly have different temporal characteristics than those shown in Fig. 1. The in-ear peak levels were 175 and 173 dB SPL for the grenade launcher and mortar, respectively. Free-field levels can be estimated at 8 to 12 dB lower than the in-ear levels [4].

For the 12.7 mm heavy machine gun, the overall peak IL results were 20.0 dB (Peltor Tactical 6-S), 41.7 dB (EAR Classic), 49.2 (ETY plugs) and 54.7 dB (EAR Classic earplug with Peltor earmuff). The 1/3 octave band ISIL for are shown in Fig. 3. The Peltor muff provided the least overall insertion loss. For the earplugs, bone conduction limits were exceeded in several frequency bands.

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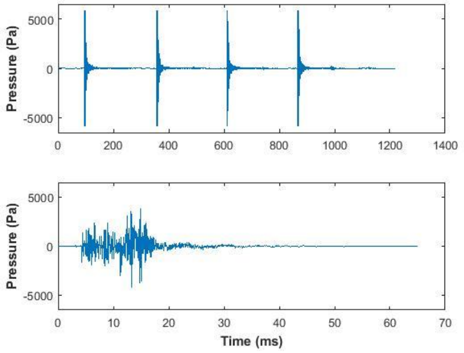

**Figure 2:** Time signals of the grenade launcher (top) and mortar (bottom) measured inside the ear of the ATF.

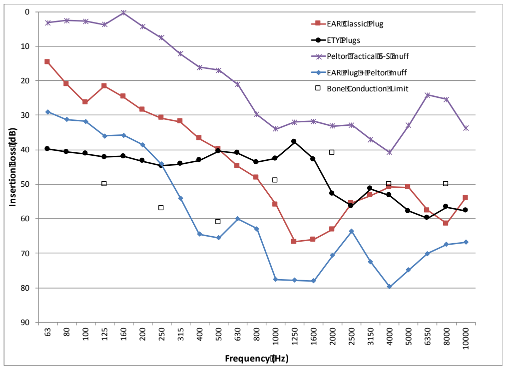

**Figure 3:** Insertion loss of passive earplugs and electronic earmuff for the 12.7 mm machine gun noise.

The ISIL for the EAR classic earplug are shown in Fig. 4 for the five weapon noise sources, as well as continuous pink noise. The earplug was least protective for the mortar and most protective for the 7.62 mm medium machine gun. Bone conduction limits were exceeded at frequencies from 1000 Hz and higher for several of the weapons and the pink noise.

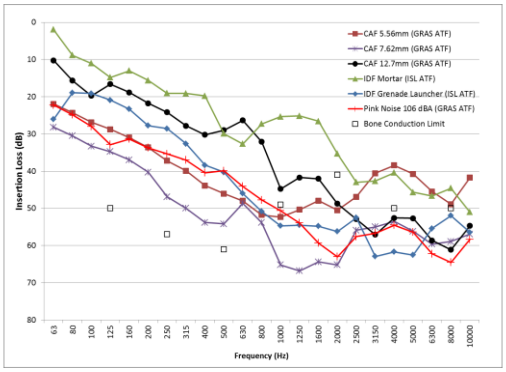

**Figure 4:** Impulse spectral insertion loss of EAR Classic plug for different noise sources.

## 4 Discussion and conclusions

The weapon noise signatures shown in Figs. 1 and 2 do not meet the ANSI/ASA standard for measuring IPIL. The A-duration, or duration of the impulse from its initial sharp increase in positive sound pressure to the time when the pressure becomes negative, is required to be between 0.5 and 2.0 ms [1]. The A-duration can only be clearly identified for the 5.56 mm rifle, and it is shorter than 0.5 ms. Although, we have not strictly followed the standard, it is important to know which HPDs work best for each weapon. The EAR classic is a very well-known example of a passive level-independent HPD. However, with different noise sources with free-field peak levels ranging from about 152 to 165 dB, different ISIL results are clearly shown in Fig. 4. In general, less protection was obtained for the heavier weapons (12.7 mm and mortar), particularly at low frequencies. This could be a concern because the noise from large calibre weapons has more energy at low frequencies [5]. However, the passive linear-attenuation earplug (ETY Plugs) provided good insertion loss for the 12.7 mm at low frequencies (Fig. 3).

An additional advantage of looking at the ISIL rather than the IPIL is that bone conduction exceedances can be seen. As shown in Figs. 3 and 4, bone conduction limits were exceeded for earplugs and double protection at frequencies of 1000 Hz and above. The IPIL can overestimate the amount of protection because bone conduction corrections are not part of the calculations [2].

It was recommended previously that the IPIL could be used account for HPDs in the assessment of noise exposure for small calibre weapons, but not large calibre weapons and blasts [6]. The current data show the importance of measuring ISIL for specific noise sources, rather than relying on IPIL data which are measured with an idealized source. We will continue collecting data for different types of weapons in order to provide better recommendations for HPD use. Additional results for more weapon types and HPDs will be presented in a follow-up paper.

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# SOUND ATTENUATION OF ACOUSTIC SHIELDS

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## 1 Introduction

Symphonic music is characterized by having wide frequency content and highly variable sound levels including high peak levels. In many occasions, the sound levels exceed 85 dBA, the golden limit for the noise to be “safe” and not posing hearing hazard.

Many studies have been conducted to measure noise exposure of classical orchestra players [1-3]. Each study found many points toward a potential risk of hearing loss and the need of some form of noise control to reduce the noise exposure of musicians. Other than the use of hearing protectors, use of acoustic shields is often recommended.

Acoustic shields are devices used for controlling sound energy reaching musicians seated in front of loud instruments (mainly brass). They consist of plastic plates, mounted on a pole and located at the head level of the musician intended to be protected. There have been studies where attenuations of those devices were measured in laboratory environments. The object of the present study was to assess the attenuation in a real-life situation, with musicians seated in an orchestra pit. This was done in our case, during 10 National Ballet of Canada performances of the ballet Le Petit Prince. Each set of measurements was done using two dosimeters: one located on the shield, and the other attached to the shoulder of the musician intended to be protected. The attenuation was obtained as the difference between both measurements.

## 2 Method

### 2.1 Participants, shields and instruments

Sixteen musicians from the National Ballet of Canada Orchestra participated in the study. They were seated in areas of highest sound levels as per the study of Qian et al [4]. Sound levels were recorded by Bruel & Kjaer personal noise dosimeters types 4445 and 4448. Each measurement consisted of a pair of readings from dosimeters located in front, where the protected musician is seated, and behind the shield. One dosimeter was set up on the shoulder of the musician seated in front of the shield to measure the musician’s actual noise exposure. The second dosimeter was set on the shield stand, positioned in the center of and 10 cm away from the shield, representing the noise exposure behind the shield.

Two types of acoustic shields are used by the orchestra: Wenger and Manhasset, model 2000. Wenger shields are made of clear polycarbonate 57 cm by 43 cm. The Manhasset shields have larger dimensions: 65 cm by 55 cm, and they are made of Lexan polycarbonate. The thickness of both types of shields is of 6 mm. Since the density of the material is 1,200 kg/m$^3$, the surface density is 7.2 kg/m$^2$, much lower than the 25 kg/m$^2$ required for a highway noise barrier. The transmission loss, according to the mass low is around 22 dB at 500 Hz.

### 2.2 Measurements

All dosimeters started recording approximately 1/4 hour before the start of each performance. They were not paused during intermissions and continued running until the end of the show. Musicians were advised not to generate any artifact noises by yelling at, breathing heavily towards, or accidentally touching the instruments.

There were a total of 27 paired measurements in this study. The attenuation of each shield was calculated as the difference of the sound exposures in dB(A) measured by the dosimeters located on both side of the shields. The performances took place at the *Four Seasons Centre for the Performing Arts*, a 2,071 seat theatre with an orchestra pit beneath the stage. The pit measures 15.5 meters in width, 6.4 meters in depth (the stage protrudes 3.3 meters over the pit, while 3 meters is unobstructed from above), and the stage is 2.4 meters above the floor of the pit.

## 3 Results

Measurements were performed in a real work situation, meaning that the influence of the location of the shield and the instruments in the perimeter of the player were not taken into consideration. All shields remained at the same location throughout the course of this study. Therefore, it cannot be definitely stated that one type of shield is better than the other because there is the possibility that both types may perform identically when located at the same spot.

The results of individual attenuations measured on both types of shields: W (Wenger) and M (Manhasset) shown in Figure 1. It shows significant variations between individual tests and an overall better performance for the Manhasset shields, compared to the Wenger. Table 1 shows a summary of the results for both shields.

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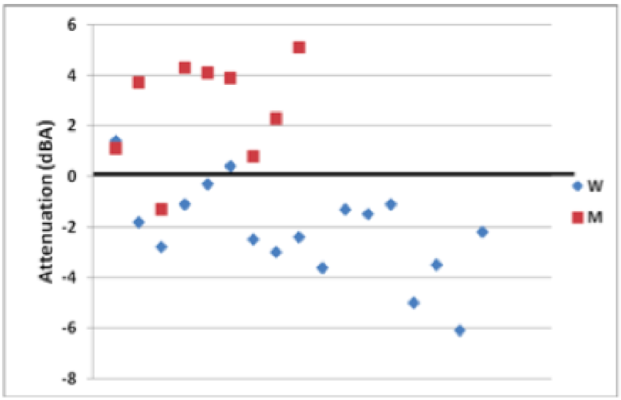

**Figure 1:** Individual attenuation

The authors were also interested in the variation of attenuations for a given shield (and same setting) during different performances. For that reason, the attenuation of some shields was repeated twice and three times while the shields selected for repeated measurements were selected at random. The average of the variations was 2 dBA, while the range was 4.0 – 0.4 dBA. Therefore variations were within the range of the accuracy of a field noise measurement and therefore not considered significant.

As expected from Table 1, the average attenuation of all shields pooled together is negative. The standard deviation is quite large, showing a large variation among attenuations.

**Table 1:** Results of the measurements

| | Wenger | Manhasset |
|---|---|---|
| **Average attenuation** | -2.14 | 2.67 |
| **St. Error** | 0.45 | 0.7 |

## 4 Conclusion

The high number of uncontrolled variables, which is generally unavoidable in a study of this kind, made it difficult to come to general conclusions. The size of the shield's surface area is too small compared to the distances from the source to the shield and from the shield to the receiver. This gives way to a larger diffraction effect around all four edges of the device. Therefore, the flow of acoustical energy around the shield becomes as significant as the flow through the shield thus significantly reducing the resulting attenuation.

The distance and the location of the head of the player behind the shield also vary during a music session due to the fact that musicians move around in their chairs during performance, resulting in an ever larger diffraction effect.

Another factor is the sound from the musicians located on the sides of the protected colleague. The shield not only offers no protection from these musicians, but may even increase their sound exposure due to sound reflected from the shields. In those circumstances, the sound of the instrument behind the musician is not as important as the lateral and front contributions, thus reducing the benefit of the shield. Sound reflection is a significant factor contributing to musicians' elevated noise exposure, and this is especially true for those musicians seated close to the walls of the pit and also because the shields are made from polycarbonate, which is a reflective material. On top of the sound coming from reflections and other musicians, there is also sound generated by the protected musician himself, that contributes to his exposure. (This may explain some or all the negative attenuation results obtained in the present study). In summary, musicians are exposed to the sound coming from their own instruments, sounds coming from other instruments, and sounds reflected by the walls, the floor, and the shields.

Results also show a significant difference between the attenuations from both types of shields. This could be caused by the difference in the size of the Plexiglas boards. The Manhasset's surface is almost 50% larger than the Wenger's, and this is something that may explain the difference in attenuation.

Finally, for this population, the attenuation was not significantly affected between different sessions. This appears to indicate that players do perform at approximately the same sound level between performances. This was already studied by Qian et al [4] who arrived at the same conclusion that the inter-performances' variations are not significant.

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# INVESTIGATION OF GROUND CREW NOISE EXPOSURE FOR THE ROYAL CANADIAN AIR FORCE CH-149 CORMORANT HELICOPTER

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## 1 Introduction

Royal Canadian Air Force (RCAF) CH-149 Search and Rescue helicopters operate in extreme and strenuous environments often with doors open configurations. Due to the demanding nature of search and rescue activities, civilians, aircrew and ground crew may be exposed to noise exposure events without properly fitted hearing protection. This paper outlines the National Research Council's (NRC) ground external noise measurement of the CH-149 Cormorant at Comox Canadian Forces Base.

## 2 Method

The exterior ground measurement involved 6 personnel in addition to the aircrew. Four, 60 second duration, measurement conditions were completed, as shown in Table 1.

**Table 1:** Measurement conditions

| ID | Auxiliary Power Unit (APU) | Engine | Avionics |
|---|---|---|---|
| **#1** | ON | OFF | ON |
| **#2** | ON | IDLE | ON |
| **#3** | ON | Flight | ON |
| **#4** | OFF | Flight | ON |

Five ICP PCB 378B02 microphones were rotated through 10 measurement locations as depicted in Figure 1. The data acquisition system selected was a Siemens LMS Test.LAB SCADAS III.

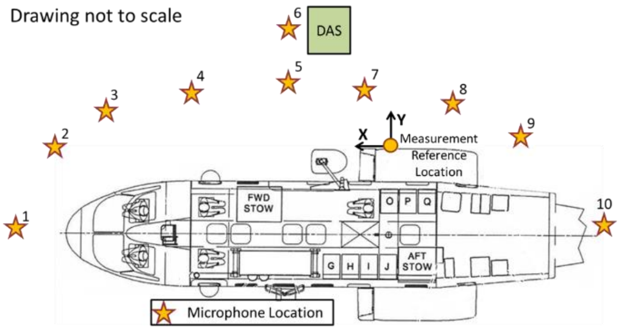

**Figure 1:** Exterior noise measurement locations

The measurement was conducted in accordance with MIL-STD-1294A Section 5.3.2.2 [1]. The microphones were mounted at a nominal head height of 1.65 ± 0.1 m and fitted with windscreens. The insertion loss of the windscreens was measured previously as a function of frequency, in the absence of wind, at the NRC Hearing Protection Evaluation Facility. The locations indicated in Figure 1 were selected to be representative of ground crew and flight engineer operations.

### Hearing protectors

In conjunction with the in-flight and ground noise measurements of RCAF aircraft, the NRC evaluated the insertion loss performance of various in-service RCAF hearing protectors at the NRC Hearing Protection Evaluation Facility. For context, six hearing protector insertion loss performance curves are shown in Figure 2 [2], [3], [4].

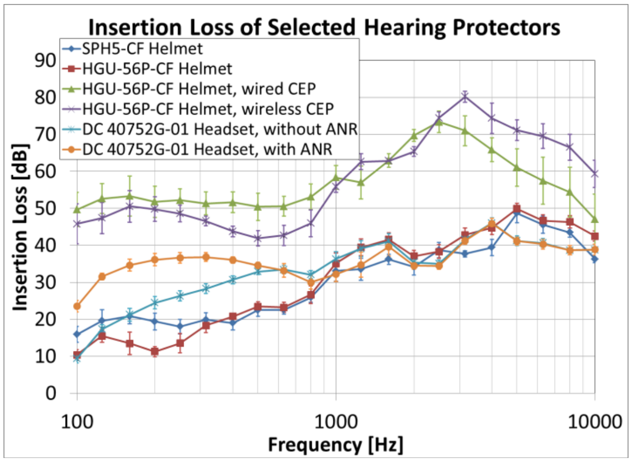

**Figure 2:** Insertion loss of selected hearing protectors

As shown in Figure 2, superior insertion loss performance was exhibited by hearing protection solutions utilizing a communication ear-plug in conjunction with a circum-aural hearing protector. It should be noted that a SPH5-CF hearing protector without communication ear plugs is commonly used in CH-149 Cormorant operations. The SPH5-CF hearing protector insertion loss is exhibited as the blue curve with diamond markers. Note that all hearing protectors exhibited superior high frequency noise reduction.

## 3 Analysis

The Sound Pressure Levels (SPL) were acquired for each measurement position and condition. The results were then post-processed and analyzed in narrow-band, 1/3rd octave

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band and Overall Sound Pressure Levels (OSPL). The OSPL data for each microphone measurement condition is exhibited in Figure 3. Additionally, the recommended maximum noise exposure dose for one 24 hour period associated with each respective OSPL in accordance with the Canadian Aviation Occupational Health and Safety Regulations [5] have been superimposed on Figure 3 as horizontal dashed lines.

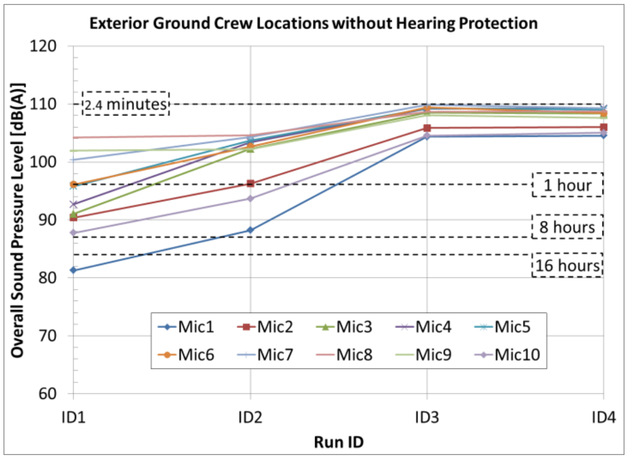

**Figure 3:** Exterior microphone OSPL levels

It is observable in Figure 3 that civilians or crew without hearing protection could be at risk of hearing damage after 2.4 minutes of cumulative noise exposure with the engines configured for flight and main rotor turning (ID 3 and ID 4). It is interesting to note that the Mic 1, Mic 2 and Mic 10 measurement locations exhibited consistently lower OSPLs. Additionally, the Mic 7, Mic 8 and Mic 9 exhibited higher OSPL levels, specifically during the ID 1 and ID 2 conditions; observing Figure 1, it can be shown that the Mic 7 - 9 locations are directly in line with the aircraft engine and APU exhaust ports. Observing the noise directivity characteristics of the aircraft when the rotors are not rotating (ID 1 and ID 2), significant reductions in OSPL can be made by avoiding specific Mic locations. Once the rotors are turning (ID 3 and ID 4) the noise environment is dominated by the N/rev rotor harmonics and the noise directivity of the aircraft environment is less prevalent.

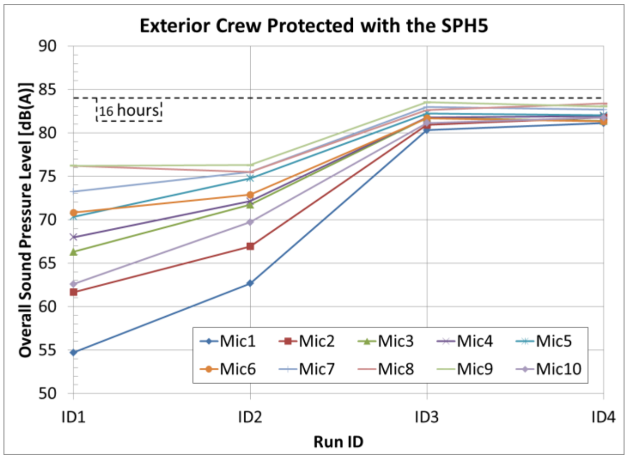

**Figure 4:** Hearing protected microphone OSPL levels

The OSPL data for each microphone measurement condition with SPH5-CF hearing protector insertion loss applied is exhibited in Figure 4. It can be shown that with a properly fitted SPH5-CF pilot helmet, all recommended noise exposure dose limits are safely in excess of 16 hours regardless of microphone measurement locations.

## 4 Conclusion

The RCAF CH-149 Cormorant Search and Rescue helicopter exhibited highly directional noise propagation during the measurement conditions without rotors turning (ID 1 and ID 2). During these conditions, a civilian or crew member can reduce their noise exposure significantly by standing near the front of the aircraft or underneath the aft tail boom (Mic 10 location). In contrast, with rotating rotors (ID 3 and ID 4), the low frequency N/rev rotor harmonic noise propagates with less sensitivity to aircraft orientation; with rotors turning, an individual without properly fitted hearing protection can exceed their maximum recommended noise exposure dose for one 24 hour period within 2 minutes and 24 seconds in accordance with the Canadian Aviation Occupational Health and Safety Regulations. When equipped with properly fitted SPH5-CF hearing protection, all exterior measurement locations exhibit maximum recommended noise exposure dose limits in excess of 16 hours.

## Acknowledgements

Great appreciation and thanks to RCAF 442 Squadron, 19 Wing Comox, DND DTAES and RCAF AETE without whom this project would not have been possible.

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# HEARING PROTECTOR FIT-TESTING: SPECTRUM UNCERTAINTY BUDGETS

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## 1 Introduction

While noise control at the source remains the objective for proper protection of workers against Noise-induced hearing loss (NIHL), hearing protection devices (HPD) are, for practical and economic reasons, often used as the first, if not the only, line of defense. In the field, however, the attenuations achieved by individual wearers of HPDs varies dramatically from these labeled laboratory values, for many reasons now well understood.

### 1.1 HPD fit-testing

To address the critical question of how much an individual users in the field are getting from their hearing protections devices (HPD), field attenuation estimation systems (FAES), colloquially referred to as “fit-testing system” have been developed over the years [1].

Because of the wide range of technologies used it was felt that a national standard would be required to ensure precision and accuracy of FAES measurement outcomes. The development of such a standard is in process under the auspices of the Acoustical Society of America (ASA) and the American National Standards Institute (ANSI), designated ASA/BSR S12.71-201x. The Working Group S12/WG 11, Hearing Protector Attenuation and Performance, has prepared an initial draft of a standard and is continuing to work to finalize this for balloting and approval [2].

### 1.2 Personal attenuation rating (PAR)

In its current draft format, ANSI S12.71 specifies minimum performance criteria for systems designed to estimate the real-ear attenuation provided by HPDs on individual users. The performance criteria are intended to ensure that FAES complying with the standard provide comparable test results to a reference laboratory procedure. Accuracy and precision are assessed by comparison of FAES data to those from the standard REAT procedure (ANSI, 2008) for the same fit of the device on an identical group of test subjects. This standard also specifies the procedures for the computation of the PAR, the personal attenuation rating. The PAR is an NRR like number, but since it is based on the data from one wearer who is the actual user of the device, instead of a group of 10-20 subjects, the between-subject standard deviation correction that is included in the NRR computation is not needed.

However, as with any single-number rating such as the NRR, the spectral variability must be accounted for. With the NRR this is accomplished using a constant 3-dB spectral safety factor, whereas the PAR accomplishes this with an explicit protection performance value that results from the variability in the computations using the 100 NIOSH noises. The PAR can be directly subtracted from A-weighted noise measurements instead of requiring the use of C weighted values as is recommended with application of the NRR. The computational details of the PAR are beyond the scope of this paper but can be found in [3] together with a comparison to other attenuation ratings and metrics.

## 2 Method

### 2.1 PAR spectrum uncertainty

PAR is expressed with its associate uncertainty that originate from three different sources: the measurement, fit and spectrum uncertainty components. The measurement uncertainty pertains to the intrinsic precision and accuracy of the FAES system in prediction the attenuation that would be measured using REAT for the same fit of the HPD under test. The fit variability pertains to the variability in the attenuation of the HPD from one fit to the next. The spectrum uncertainty arises when a fit-test system provides a single number such as a PAR that is to be applied to A-weighted sound level measurements of noises with unknown spectral content. Depending on the actual noise spectral content, there can be a variation between the attenuation predicted using an octave band calculation (usually on 7 octave-bands) applied to the actual octave-band noise data, versus that achieved with a PAR, which is analogous to the single number approach described in ANSI S12.68 [4]. The spectrum uncertainty can be easily obtained by computing the difference between the incident A-weighted sound levels and the A-weighted sound levels effective when the HPD is worn, over all the noise of NIOSH 100 database of industrial noise spectra [5].

### 2.2 Spectrum uncertainty budget

In the field, when a FAES is used, the calculation of the spectrum uncertainty has to be performed for every HPD attenuation estimation. This can be rather computationally intensive and it also requires that the FAES used do actually provide attenuation estimates at two or more octave-band frequencies.

It is therefore proposed in this study to ”budget” for such spectrum uncertainty value, by computing for every type of HPD, a conservative -but representative- value of spectrum uncertainty. For this reason, attenuation values of representative HPD samples, measured in laboratory

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conditions and listed in the Hearing Protector Device Compendium Database.

The exact method used for the offline computation has been presented in [6] and is reused in the present study, for roll-down foam, pre-molded, formable, semi-inserts and earmuffs, as well as two other categories of hearing protectors: the custom molded earplugs and the push-to-fit earplugs. Consequently some FAES system with limited signal processing resources or with a measurement method that does not provide at least two octave-band attenuation values, may not have the ability to compute the spectrum uncertainty associated with the PAR of the HPD under test.

## 3 Results

These cumulative distributions of spectrum uncertainty are computed using Matlab (Mathworks, Natick, MA, USA) scientific programming software for a total of 353 HPDs: the 33 semi-insert, the 42 pre-molded earplugs, the 66 foam earplugs, and the 245 earmuffs present in the NIOSH Hearing Protector Device Compendium Database (while the total number of records from the NIOSH database was actually 386, due to tests reported for multiple position there were 340 distinct products), together with 7 custom-molded earplugs and 6 push-to-fit earplugs added by the author from the most recent online version of the NIOSH HPD Compendium. These distributions are plotted in Fig.1, on a range of 0 to 5 dB. Descriptive statistics have also been obtained on the different values of spectrum uncertainty computed for the various types of HPDs and are presented in Table 1.

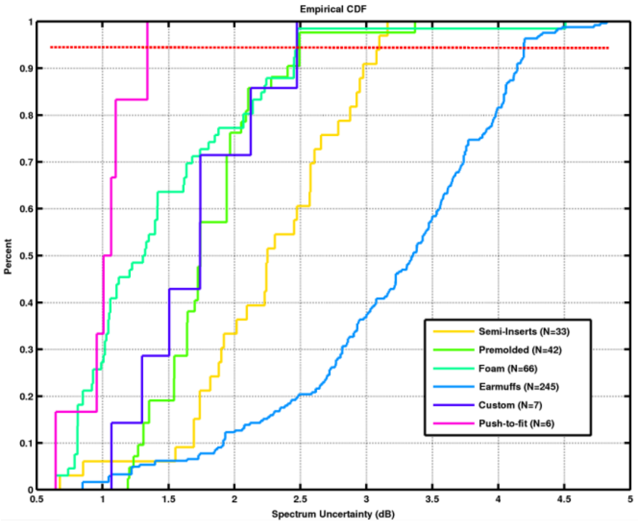

**Figure 1:** Empirical cumulative distribution function of the spectrum uncertainty computed for each of the six types of HPDs.

It can been seen from Fig. 1 that the spectrum uncertainty value for 353 HPDs representative of current product on the market is ranging from 0.4 dB to 4.8 dB. This upper value seems to be sometimes driven by only a few product samples within one type of HPDs. It is therefore proposed to express the spectrum uncertainty budget, i.e. by using the 95th percentile value of the cumulative empirical distributions plotted in Fig. 1. From the empirical distribution values, the 95th percentile value of the spectrum uncertainty, represented by a red horizontal line in Fig.1., is respectively of 3.09 dB, 2.49 dB, 2.48 dB, 4.19 dB, 2.47 dB, and 1.34 dB for semi-inserts, pre-molded earplugs, roll-down foam earplugs, earmuffs, custom molded earplugs and push-to-fit earplugs.

**Table 1:** Number of observations and empirical distribution parameter estimates for the spectrum uncertainty data of the different HPD types.

| HPD Type | Semi-Inserts | Pre-molded | Foam | Earmuffs | Custom | Push-to-Fit |
|---|---|---|---|---|---|---|
| N | 33 | 42 | 66 | 245 | 7 | 6 |
| min | 0.68 | 1.19 | 0.65 | 0.85 | 1.07 | 0.65 |
| max | 3.16 | 3.37 | 4.51 | 4.82 | 2.47 | 1.34 |
| mean | 2.26 | 1.82 | 1.45 | 3.18 | 1.71 | 1.02 |
| median | 2.25 | 1.74 | 1.32 | 3.35 | 1.74 | 1.04 |
| std deviation | 0.61 | 0.43 | 0.68 | 0.87 | 0.48 | 0.23 |
| 90th percentile | 3.00 | 2.43 | 2.45 | 4.14 | 2.40 | 1.32 |
| 95th percentile | 3.09 | 2.49 | 2.48 | 4.19 | 2.47 | 1.34 |

## 4 Conclusions

The study included a detailed spectrum uncertainty budget for the various categories of earplugs (roll-down foam, pre-molded, formable, custom molded, push-to-fit, etc.), semi-inserts and earmuffs. These values have been expressed at the 95th percentile for a direct use in the upcoming ANSI S12.71 standard and will be useful for FAES that cannot perform the computationally intensive octave-band calculation of PAR spectrum uncertainty.

## Acknowledgments

The author would like to thanks CAPT William J. Murphy for facilitating access to the 2004 version of the HPD Compendium database from NIOSH and would like to acknowledge the highly motivating spirit of ANSI S12Working Group 11, chaired by Mr. Elliott H. Berger.

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# ABSTRACTS FOR PRESENTATIONS WITHOUT PROCEEDINGS PAPER
# RÉSUMÉS DES COMMUNICATIONS SANS ARTICLE

## The Iso Standard On Hearing Protectors

*Alberto Behar*

The International Organization for Standardization (ISO) has the "ISO 4869 Acoustic – Hearing Protectors" standard that deals with everything regarding hearing protectors. It is an omnibus document divided in six parts as follows: Part 1: Subjective method for the measurement of sound attenuation Part 2: Estimation of effective A-weighted sound pressure levels when hearing protectors are worn. Part 3: Measurement of insertion loss of ear-muff type protectors using an acoustic test fixture Part 4: Measurement of effective sound pressure levels for level-dependent sound-restoration ear-muffs Part 5: Method for estimation of noise reduction using fitting by inexperienced test subjects Part 6: Determination of sound attenuation of active noise reduction ear-muffs. Standards are required to be reviewed and updated periodically, usually within 5 years. Parts 1, 2 and 6 have been examined at the last meeting of the Working Group 17, Hearing Protectors. In our presentation we will focus on some of the above documents that are of special interest to Canada.

## The History Of Real-Ear Attenuation At Threshold Since 1957 With Emphasis On The Most Recent Ansi S12.6-2016 And Csa Z94.2-2014 Standards

*Elliott H Berger*

The American standard specifying the procedure for the measurement of real ear attenuation at threshold (REAT), often termed the gold standard in measuring hearing protector attenuation, was approved last year as an updated version, ANSI 12.6-2016. REAT was first standardized worldwide in the late 1950s in an American standard ANSI Z24.22-1957 and the method has evolved with time. Changes have affected the electroacoustic requirements for the sound field, instrumentation, audiometric method, and permissible background noise, but more importantly have also improved the specification of how the experimenter works with and fits the test subjects. So too, estimates of uncertainty are now included, and in the 2016 version they have been clarified and brought into harmony with ISO 4869 1. The ANSI standard also impacts Z94 since the latter standard references S12.6 for specification of the Canadian methodology. The author, who has been the chair since 1985 of the ANSI working group responsible for S12.6 and a member of the CSA working group responsible for Z94 since 1981, will compare and contrast the various methods and the Z94 requirements, and present representative data as well as a discussion of the expanded uncertainties that are specified in the most recent ANSI and ISO documents. Those values, for the 1/3 octave band test bands from 125 Hz to 8000 Hz, vary from approximately 1.5 2 dB for earmuffs and 2-3 dB for earplugs for within-laboratory testing, to 4-6 dB for earmuffs and 6.5-8 dB for earplugs for between laboratory measurements.

## Occupational Health Considerations For Teachers In Music Classrooms

*Stephanie Seebach, Darron Chin-Quee*

Music classrooms require a balance between instructional uses requiring speech and musical uses, which often have divergent acoustical objectives in terms of reverberation and shape. A further complication in designing these spaces considers the occupational health and safety issues for music teachers who are exposed to intrinsically high levels of sound for up to 6 hours a day. This paper examines the noise environment and sound exposure of music teachers relative to Occupational Health and Safety Regulations. The effectiveness of various strategies for reducing the sound exposure of music teachers including the use of architectural controls and hearing protection are discussed. Case studies involving a few music classrooms are provided to illustrate some of the common issues encountered.

## Localization Of Reverse Alarms With Personal Safety Equipment

*Véronique Vaillancourt, Christian Giguère, Chantal Laroche, Hugues Nélisse*

Several factors can contribute to the occurrence of accidents involving reversing heavy vehicles, despite the mandatory use of reverse alarms in many workplaces. Among others, reverse alarms can be difficult to localize in space, which may lead to errors in adequately identifying the source of danger. Previous studies have shown that traditional reverse alarms ("beep-beep") are more difficult to localize in space than broadband alarms ("pschtt-pschtt"). In addition, personal safety equipment such as hearing protection devices and safety helmets, often required in noisy workplaces where reverse alarms are used, may potentially further impair localization.

This study explored the effect of passive hearing protection devices (earplugs, earmuffs and double protection) and use of a safety helmet on the ability of normal-hearing individuals to localize the two types of reverse alarms, in background noise, while performing a task. Consistent with previous findings, the broadband alarm was easier to localize than the tonal alarm. While passive hearing protection can have a significant impact on sound localization (with a marked degradation in performance with double protection), use of a safety helmet has a more limited effect. Preliminary results from a study using the same methodology with level-dependent (sound restoring) hearing protection devices are also presented.

## Going Global: Hearing Conservation Regulations And Trends

*Laurie Wells*

Noise is recognized universally as an occupational hazard which can cause permanent hearing loss, tinnitus, and other negative health effects. However there isn't a globally accepted regulatory or best practice approach toward protecting the noise-exposed workforce. The regulatory differences for hearing conservation around the world make it challenging for multinational companies to set policies for corporate hearing loss prevention programs. This presentation compares and contrasts selected aspects of various hearing conservation regulations to the United States Occupational Safety and Health Administration (OSHA) requirements. The following jurisdictions are included: Australia/New Zealand, Brazil, Canada, China, European Union, India, Japan, and Mexico. Details were collected from English translations of a country regulation as well as by consultation with an experienced, in-country resident whenever possible. Regulatory content includes: noise exposure limits, noise control requirements, hearing protection device use, standards, and attenuation derating schemes, audiometric testing and hearing shift criteria, and worker training requirements. In addition, some emerging trends in hearing loss prevention practices will be highlighted including noise measurement criteria, fit testing of hearing protection, the role of the audiologist or physician as the professional supervisor of an audiometric monitoring program, and the observed transition of noise induced hearing loss from an occupational disease to a public health issue. Studying the various regulatory approaches and noting practical application trending can spark discussion as to best practices and recommendations for employers.

# SHOCK AND VIBRATIONS - CHOCS ET VIBRATIONS

# MITIGATION OF RAILWAY INDUCED GROUND-BORNE NOISE AND VIBRATION

**Rabih Alkhatib**[*1], **A. D. Lightstone**[*1] **and Sam Du**[*1].
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## 1 Introduction

New surface and underground railway and rail transit lines are increasingly being introduced into urban areas as a result of intensification. Furthermore, new developments are being built with lighter construction materials and longer spans in close proximity to track alignments. This has led to more ground-borne noise and vibration being perceived inside buildings and increased potential for annoyance to the occupants. Vibrating walls and floors act like giant loudspeakers reradiating the acoustic energy as sound (noise). Low levels of vibration, even below the level of human perception can interfere with the operation of sensitive equipment found labs and high-tech facilities.

There are alternative methods to mitigate the impact of ground-borne noise and vibration from railway traffic which can be used individually or together: isolating the source, interrupting the vibration path and/or isolating the receiver.

The recommendations described hereafter arise from the past experience with railway ground-borne noise and vibration assessment and design for various projects.

## 2 Controlling vibration at the source

The dynamic interaction between the vehicle wheels and the rails is the source of ground-borne noise and vibration produced by railway traffic. Worn wheels, worn tracks, and special trackwork such as turnouts and switches will increase the level of interaction. Furthermore, some vehicle parameters such as the primary suspension system stiffness has a direct effect on the level of vibration being generated. Reduction of noise and vibration at source can be achieved by eliminating the running surface discontinuities, regular maintenance of the rail running surface, regular wheel re-profiling, and selecting the appropriate type of rail vehicle. Track vibration isolation can be achieved through the installation of resilient elements in the track superstructure.

### 2.1 System consideration

**Rail grinding and replacement**

Rail corrugation and irregularities developed over time cause increases in the ground-borne noise and vibration. Instituting a regular rail grinding and replacement program will prevent increase of noise and vibration associated with rail wear.

**Wheel re-profiling and replacement**

Hard braking can cause flat spots on the vehicle wheels which is termed “wheel flats”. Impacts from damaged wheels lead to significant increases in ground-borne noise and vibration. Grinding wheels with flat spots to round will eliminate the impacts caused by such wheels and reduce wheel/track dynamic interaction.

**Vehicle specifications and maintenance**

Unsprung weight (axles and wheels) and stiffness of primary suspension system are important factors in train induced vibration. Rail vehicles should be designed with low unsprung weight and soft primary suspension (vertical resonance frequency less than 15 Hz) to minimize dynamic forces generated by wheel/track interaction.

**Location and design of special trackwork**

Special trackwork such as turnouts and crossovers allow trains to switch from one track to another. This can be a major source of noise and vibration. When feasible, locating crossovers and turnouts away from sensitive land uses can be an effective mitigation measure. Another approach is to install spring-loaded frogs to eliminate gaps at crossovers and help reduce vibration levels.

### 2.2 Isolating the track

Vibration Isolation of the track has been effectively used to mitigate ground-borne noise and vibration. Increasing the track flexibility, by introducing resilient elements into the track system, reduces dynamic forces at the track support and thereby reduces the vibration propagating towards nearby buildings. Conventional railway track consists of sleepers (crossties) of wood imbedded in a bed of gravel (ballast), with the track fastened to the sleepers with steel spikes. Other systems use concrete slabs or segments in place of the sleepers.

**Resilient rail fasteners**

Resilient fasteners are used to fasten the rails to the sleepers or to the concrete track slabs. An elastomer pad which is part of the fastener system is inserted under the rail to reduce the vertical stiffness of the rail and therefore reduce the ground-borne vibration by as much as 4 to 8 dB at frequencies above 30 to 40 Hz. Highly resilient rail fasteners involve an elastomer component that mostly acts in shear under typical train loads.

**Resilient sleepers/crossties**

Resilient sleepers consist of concrete sleepers with rubber pads directly attached to the underside of the sleepers which

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sit on the ballast. The rails are fastened directly to the concrete sleepers using Direct Fixation (DF) fasteners. With relatively soft rubber pads between the sleepers and the ballast, it is possible to reduce the vibration by at least 5 to 10 dB at frequencies above 30 to 40 Hz

**Booted sleepers/crossties**

The booted sleeper systems consist of concrete sleepers encapsulated by elastic boots that are embedded into the concrete slab track. Booted sleepers act in similar manner as resilient sleepers but the design is integrated with a slab track. They are typically effective in reducing vibration by up to 10 dB in the frequency range of 20 to 30 Hz.

**Ballast mats**

Ballast mats are one of the most effective methods of reducing vibration transmission from ballasted track. It consists of relatively soft elastomer pad that is placed under the ballast. Ballast mats are less effective if placed directly on the soil or the sub-ballast. Depending on the soil properties, an asphalt or concrete layer under the ballast may be required. Ballast mats can provide between 10 to 15 dB vibration attenuation at frequencies above 25 to 30 Hz.

**Tire-derived aggregate (TDA)**

Made from shredded rubber tires, a typical TDA installation consists of 300 mm thickness of TDA (nominal 75 mm tire shreds or chips) wrapped with geotextile fabric placed on compacted subgrade and covered with 300 mm of sub-ballast and 300 mm of ballast directly beneath the sleepers. This type of mitigation can only be used on ballasted track. Field tests indicate that the vibration isolation effectiveness of TDA is midway between that of the most effective ballast mat and the floating slab track.

**Floating slab track**

A floating slab consist of a concrete slab supported on resilient elements such as discrete rubber pads, continuous elastomer mats, or steel coil springs. The track is attached to the concrete slab using Direct Fixation (DF) fasteners or embedded track. The resilient elements are supported on a concrete foundation. Floating slabs can be very effective at controlling ground-borne noise and vibration down to frequencies near 5 Hz. This type of track construction is costly and is typically used only where significant vibration mitigation is needed. Floating Slab Track can provide 15 to 20 dB vibration attenuation.

**Design considerations**

Isolating the track superstructure involves increasing the track compliance and therefore increasing the track deflection under the train load. Sudden change in track stiffness should be avoided as it lowers the fatigue life of the rails and degrades the ride quality of passengers. A transition zone with gradual stiffness change should be installed around mitigated section of the track.

Soil stratification and properties are important factors in determining the effectiveness of any of the above isolation methods. Calculation of the track stiffness with and without isolation should include an estimate of soil compliance.

The reduction in ground-borne vibration provided by any of these measures is heavily dependent on the frequency content of the vibration. Vibration measurements show various trains have different dominant frequencies. For any of the vibration isolation methods to work, the natural frequency of the isolation system should be well below the dominant frequency of vibration.

## 3 Controlling the transmission of vibration

Vibration waves diminish as they travel away from the source because of geometric spreading and soil material damping. Amplitude of vibration is inversely proportional to distance from railway tracks. Therefore, setback distance can be an effective mitigation measure against ground-borne noise and vibration. In new developments, locating the sensitive land use away from the alignment can reduce vibration impact.

For existing structures, ground vibration from rail operations can be reduced through the installation of trenches between the track and the building foundations in a similar manner to noise barriers. Trenches can be filled with materials such as foamed insulation board designed for below-grade use. Solid barriers can be constructed with sheet metal piles, rows of drilled shafts filled with either concrete or a mixture of soil and lime, or concrete poured into a trench. . Trenches typically are effective in reducing vibration from surface railway operations but have insignificant effect when it comes to vibration generated by subway lines.

## 4 Controlling vibration at the receiver

Vibration isolation of building foundation and footings using resilient elements, rubber bearing pads, or steel coil springs can be utilized to prevent vibration waves from being transmitted into building’s interior. Although complicated, to avoid flanking, this approach can be particularly effective for buildings above transit lines or very close to subway or surface alignment. Vibration isolation of buildings is only practical for new development and unlikely to be used for existing buildings.

Alternatively, in non-residential buildings, the floor upon which vibration-sensitive equipment is located could be stiffened and isolated from the remainder of the building. Sensitive equipment could be locally isolated from the floor and building using special isolation equipment such as air spring isolation tables.

## 5 Conclusion

Controlling vibration at the source is considered the most effective method in mitigation of railway traffic induced ground-borne noise and vibration. However for new development near existing alignments, other methods should be considered such as building base isolation.

# CASE STUDY: COMPARING MEASURED AND FINITE ELEMENT MODELLED FOOTFALL VIBRATION LEVELS IN A NEW RESEARCH BUILDING

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## 1 Introduction

Occupant footfalls are often the most critical source of floor vibration on the elevated floors of buildings. In research facilities employing high resolution electron microscopes, this issue can be critical. Vibration impacts on sensitive equipment are best addressed during the design stage, relying on prediction methodologies to determine the building's response to footfall vibration.

This paper presents a case study of the measured vs. predicted footfall vibration levels on elevated, bare concrete floors, prior to completion of the extension of the Brimacombe Building which is associated with the Stewart Blusson Quantum Materials Institute at the University of British Columbia (UBC). The facility requires a low vibration environment to support world-leading quantum materials research. The building is entirely concrete; the most vibration-sensitive equipment is housed in the basement which has been isolated from the surrounding soil by engineered sub-soils and a 50 mm thick layer of Regupol Vibration 450 isolation material [1]. Level 1 (L1) consists of a 450 mm slab supported on shear walls spaced at 6.4 m. Levels 2-4 (L2-L4) consist of a 350 mm thick slab with 6.4 m x 9.8 m bays.

## 2 Methodology

Both the prediction methodology and the measurement methodology used the following loading conditions:

- Walking at 108 steps per minute (slow) within same bay as measurement.
- Walking at 132 steps per minute (fast) within bay adjacent to measurement location.

Pedestrian weight was normalised in both cases to 746 N by multiplying the measured levels by 746 divided by the walker's weight. One test location on each of the four elevated levels (L1-L4) was measured.

### 2.1 Prediction methodology

**The concrete centre (CCIP-016)**

The CCIP-016 methodology predicts vertical vibration induced by pedestrians crossing structures such as floors and bridges. It uses a Finite Element (FE) approach based on principles of modal analysis, and is considered a robust approach for the assessment of any type of structure of any construction material [2].

The CCIP considers the resonant and impulsive response of a floor to footfall forces. The modal responses at the locations of the footfall force and the receiver point are used to determine the response of the floor, at any point, based on a footfall force applied at any point. The method uses modal superposition to determine the combined effect of many modes. The response can be determined in the time domain or converted to a frequency-domain format. In this paper the data has been processed using one-third octave frequency spectra. A damping ratio of 3% was chosen to suit the building design in accordance with Table A2 in CCIP-016.

### 2.2 Measurement methodology

Field measurements, using the same receiver and loading locations used for the CCIP predictions, were performed. Site conditions dictated that the receiver locations were slightly different between each floor with reference to the centre of the structural bay. The site was unoccupied during the measurements and construction was incomplete and varied by floor from inclusion of ducts and framing (L1) to no ducts or framing (L4). Construction equipment and building supplies loaded the floors. Three single-axis accelerometers were mounted on the bare concrete floor in a tri-axial configuration for each receiver location. Two subjects performed walking tests along a path not closer than 1.2 m from the sensors. The pedestrians were prompted to maintain a constant pace rate by a metronome.

## 3 Vibration criteria

The vibration criteria (VC) curves described by Amick et al [3] are expressed as the root mean square (RMS) values of each one-third octave band from 1 Hz to 80 Hz and range from VC-A (least stringent) to VC-G (most stringent). The target criteria for the UBC project was VC-C at L1 and VC-A at L2, L3, and L4.

## 4 Predicted vs. measured floor vibrations

The following metrics were compared between the CCIP-016 predictions and the field measurements:

- Natural Floor Resonance
- Damping Ratio
- Vibration Class – Fast Walking Speed
- Vibration Class – Slow Walking Speed

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## 4.1 Natural floor resonance and damping ratio

### Natural floor resonance

The natural frequencies of the modelled floor were extracted from the FE model. The natural frequencies of the measured floors were determined by measuring the responses of the floors to a series of heel drop impulses at the receiver locations. These responses were converted to the frequency domain and the predominant response frequency was taken to be the natural frequency of the floor.

### Damping ratio

The CCIP-016 predictions assumed a 3% damping ratio (fixed across all frequencies) on the basis of the site conditions described above. Actual damping ratios in the field are difficult to estimate accurately due to frequency-dependent and non-linear behaviour. However, they were estimated at the receiver locations by applying a bandpass filter to the measured heel drop responses at the predominant response frequency and fitting a logarithmic decrement curve to the data points. A comparison of the measured vs. predicted metrics are shown in Table 1 below.

**Table 1:** Measured vs. predicted floor properties

| Level | Predicted | | Measured | |
|---|---|---|---|---|
| | Frequency (Hz) | Damping Ratio(%) | Frequency (Hz) | *Damping Ratio(%) |
| L1 | 58.6 | 3.0 | 42 | 1.5 |
| L2 | 10.9/19.2 | | 11 | 2.8 |
| L3 | 10.9/11.9 | | 10.25/12 | 2.0 |
| L4 | 9.8 | | 8.5/11.25 | 4.7 |

* Damping ratio at measured natural frequency

Note: Although L2-L4 are structurally similar, the receiver locations varied by floor causing variation in the natural frequency and vibration levels.

## 4.2 Vibration class

The results of the CCIP-016 time series predictions as well as the measured vibration levels at each receiver location were spectrally analysed and plotted against the VC criterion. The measured data was analyzed using 1 s windows and the maximum response in each frequency band was returned. The resulting VC classes for each receiver location are presented for both walking speeds in Tables 2 and 3.

## 5 Discussion

The predicted results at L3 and the predicted slow results at L2 were accurate (within the same class).

At L1 the CCIP-016 method over-predicted the slow walking response and under-predicted the fast walking response. The exceedance of predicted results for the fast walking scenario could be partially explained by the very low levels of vibration on this floor which mean that the measured levels could easily be influenced by external vibration sources. Additionally, it is not unexpected that the CCIP-016 method had difficulty predicting the response in this location as it is unlikely the method has been validated for floors this stiff. The shear walls supporting this space were modelled as fixed connections and it is possible that more flexibility is present at these connections which could change the mode shapes and thus alter the results.

**Table 2:** Measured vs. predicted vibration class – Slow walking

| Level | Predicted | Measured |
|---|---|---|
| L1 | VC-C | VC-D |
| L2 | VC-A | VC-A |
| L3 | VC-B | VC-B |
| L4 | VC-B | VC-A |

**Table 3:** Measured vs. predicted vibration class – Fast walking

| Level | Predicted | Measured |
|---|---|---|
| L1 | VC-E | VC-D |
| L2 | VC-B | VC-C |
| L3 | VC-C | VC-C |

Note: Fast walking test was not possible on L4 due to construction materials and equipment blocking the walkway.

At L2, the model predicted a natural frequency at 19.2 Hz which is what resulted in the maximum predicted result in the fast case. In the measured results, the 19.2 Hz mode was not dominant. This resulted in the model over-predicting the expected vibration.

At L4, the model under-predicted the vibration response. This is an unexpected and unusual outcome. This measurement was recorded closer to the support column than measurements L2 and L3, the structure was loaded significantly with construction materials, and the structure is the same on Levels 2-4; thus, it would be expected that the natural frequency would be lowered by the added mass but the proximity to the support column would provide a lower vibration level than those measured at L2 and L3. Without further measurements it is difficult to draw meaningful conclusions from this unexpected result.

## 6 Conclusion

The results of this study indicate that the CCIP methodology is robust and provides reasonable estimates of the floor vibration response. In all cases, the predicted and measured vibration levels meet the building design targets.

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# SUBWAY TRAIN-INDUCED NOISE AND VIBRATION IN BUILDING: PREDICTIONS AND MEASUREMENTS

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## 1 Introduction

Urbanization ensures that noise and vibration from rail and metro lines will continue to be an important field of research as structures coexist with nearby rail lines. The transmission of train-induced noise and vibration through building remains an active field of research. This ongoing research is largely due to the complexity of modelling the transmission of broadband vibration through the soil, into the building's foundation, and within the building itself. There are numerous approximate methods, empirically-derived models, and detailed finite and boundary element approaches available to predict train-induced vibration levels within buildings; however, the uncertainty associated with these predictions remain large, and few have been extensively evaluated with measurements.

The current study investigates the transmission of noise and vibration in a 17-storey reinforced concrete building located adjacent to the Toronto Transit Commission (TTC) Yonge-University (Line 1) and Bloor-Danforth (Line 2) lines. Vibrations are measured on the building's foundation adjacent to the metro line, and simultaneously, noise and vibration levels are measured on three elevated floors. Dozens of train passes are recorded over a measurement period of several hours, and they are observed to be the dominant source of noise and vibration within the building. In this paper, the results of the measurement program are presented, and are compared to simple rail vibration and noise prediction methodologies. These measurements add to the limited but growing body of published in-situ measurement data that is necessary to evaluate predictive models for train-induced vibrations.

## 2 Method

### 2.1 Measurements

Noise and vibration measurements are conducted on a 17-storey reinforced concrete building that is adjacent to the TTC Yonge-University (Line 1) and Bloor-Danforth (Line 2) lines. A 16-channel dynamic data acquisition system was used to record at sampling frequency of 3200 samples/second, which is sufficient to capture the typical noise and vibration frequencies produced by trains. Table 1 summarizes the locations of the accelerometers (Accel) and microphones (Mic) used in this study.

A tri-axial accelerometer was placed in the sub-basement parking garage adjacent to the subway line, enabling the vibration levels measured at this location to be taken as the input vibrations. Vibrations are also measured on the ground floor, as well as levels 1 and 2. Microphones are also positioned near the accelerometers on all levels. Only vertical vibrations are considered in this study. Vertical vibration may propagate through the building to higher structural levels through either shear walls or concrete columns.

**Table 1:** Location of sensors.

| Sensor Type | Level |
|---|---|
| Tri-axial Accel / Mic | P2 (sub-basement) |
| Tri-axial Accel / Mic | G (ground floor) |
| Tri-axial Accel / Mic | L1 (level 1) |
| Vertical Accel / Mic | L2 (level 2) |

### 2.2 Modelling

Simplified models are employed to predict the vibration transmission within the building. The US Department of Transportation – Federal Transit Administration provides a simplified vibration assessment methodology [1]. Using qualitative descriptors of the vibration source, soil, and building, vibration attenuations and amplifications are applied to a baseline level of vibration to estimate the vibration levels that will be experienced by building occupants.

An impedance model was also employed to predict the vibration transmission through the structure [2]. The model simplified the building to be represented as an axial rod, representing a building column, with lumped masses at the locations of the floor slabs. The frequency-dependent mass and stiffness matrices are then created and used to determine the system response to a unit input at the base. Transfer functions are then generated, which can be used to predict vibration levels within the building if the base excitation is known.

## 3 Results

### 3.1 Measurement results

The measured vibrations are post-processed into 1/3-octave bands of the RMS response. Using the vibrations at level P2 as the input signal, transfer functions are created to assess how vibrations propagate to levels G, L1 and L2. Figure 1 shows the transfer functions generated from a ½-hour record during which approximately one dozen train

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passes occurred. The transfer functions generated by independent measurement records were found to be consistent with those of Fig. 1.

Fig. 1 indicates that vibrations at frequencies less than approximately 10 Hz do not attenuate at the ground floor (G) and level 1 (L1), however the vibrations at level 2 (L2) are reduced by over 50%. A resonant amplification appears to occur on floors G and L1 in a frequency range of 20-50 Hz. L2 shows a small amplification between 10-20 Hz.

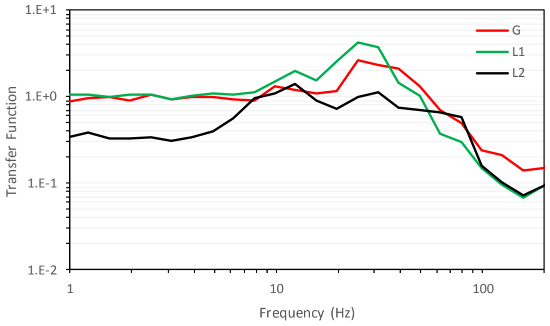

**Figure 1:** Measured transfer functions relating vibrations in P2 to levels G, L1, and L2.

## 3.2 Measurement results vompared to FTA general and detailed assessment methods

A comparison of the overall vibration ("Vibn") and sound pressure ("SPL") levels shows good agreement with the FTA general vibration assessment results:

**Table 2:** FTA General Assessment Prediction Results

| Location | Measured (Vibn / SPL) [VdB re µin/s / dBA] | FTA (Vibn / SPL) [VdB re µin/s / dBA] |
|---|---|---|
| P2 (sub-basement) | 76 / 51 | 75 / 42 |
| G (ground floor) | 73 / 44 | 73 / 38 |
| L1 (level 1) | 72 / 34 | 71 / 36 |
| L2 (level 2) | 68 / 37 | 69 / 34 |

The measured sound pressure levels at P2 and G are significantly higher than the FTA general assessment results, likely due to the larger room volume and longer reverberation time in these spaces, which do not comply with the assumptions included with the FTA model.

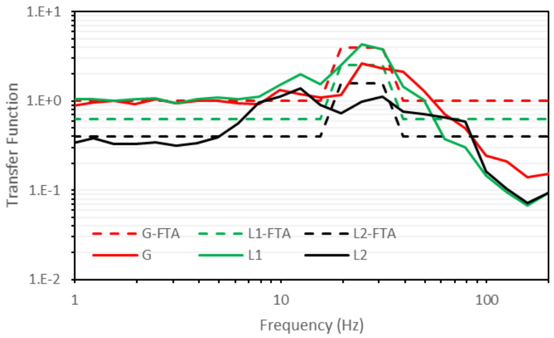

**Figure 2:** Predicted (FTA detailed) and measured transfer functions relating vibrations in P2 to levels G, L1, and L2

Taking the measurements at P2 as the force-density, and assuming negligible reduction in vibration due to horizontal distance from P2 to G, L1 and L2; the transfer functions to levels G, L1 and L2 were calculated based on the FTA detailed assessment methodology. As seen in Fig. 2, the modelled results are also in fairly good agreement with the measurement results.

## 3.3 Measurement results compared to impedance model method

Fig. 2 shows the measured results plotted alongside those predicted by the impedance model. This simplified model does not accurately predict the measured vibration amplifications on levels G and L1. Rather, the model predicts very little vibration amplification or attenuation of the floors considered over the frequency range shown.

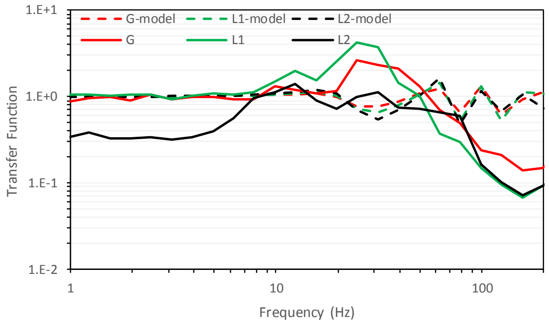

**Figure 3:** Predicted (impedance model) and measured transfer functions relating vibrations in P2 to levels G, L1, and L2.

# 4 Conclusion

Three rail vibration propagation prediction techniques are compared to measurement results in a steel and concrete structure (levels P2, G, L1 and L2). The FTA general assessment method does not require site measurements, and the results are in good agreement with the overall vibration and sound level results; however, the model lacks spectral detail. The FTA detailed assessment results include spectral predictions based on site measurements and general assumptions of the building characteristics. The results are within a reasonable agreement with the measurement result. Increased detail in the potential for floor vibration amplification would improve accuracy of the model.

The impedance model does not require measurements and yields spectral detail, however the results in this case are not in good agreement with the measurement results. Further refinement of this model should be investigated.

# References

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# PROTECTION OF CRITICAL ASSETS FROM CONSTRUCTION VIBRATION: FIELD TESTS, PREDICTION, AND CONTROL

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## 1 Introduction

This paper presents the results from vibration testing and modelling conducted during the design of a major hospital complex expansion adjacent to a research facility. The expansion will include construction of several multi-storey buildings with shoring, construction of raft slabs and Franki pile-supported slabs, and large-scale compaction. The research facility houses many sensitive laboratory equipment as well as a vivarium at basement level. Protection of research assets is a major concern during construction as ground-borne vibrations can affect performance of sensitive equipment, disrupt long-term experiments (e.g., cell culture development), and impact the health of the animals.

As Vibration Consultants on the project, the authors were responsible for developing vibration control specifications to ensure appropriate protection of the research facility and surrounding land uses during demolition and construction. This included development of a construction vibration model to predict vibration levels during various demolition and construction activities based on coordinated testing at the site.

## 2 Coordinated site testing

Two separate sets of construction tests were carried out to determine site specific ground propagation properties, building attenuation characteristics, and to obtain qualitative feedback from users during tests.

### 2.1 Excavator and plate compactor

The first phase of testing was carried out using an excavator armed with a plate compactor to apply impacts and vibratory compaction to the ground at the surface and at a depth corresponding to the depth of new building foundations.

Vibration monitors were installed at six locations within the research facility and at the base of the building foundation as shown in Figure 1.

### 2.2 Pile driving

Preliminary modelling was conducted following the first phase of tests to establish potential impacts of Franki Piling. Model parameters were extracted from the excavator testing as well as historical measurements of Franki pile installations at other sites. The results indicated that the installation of Franki piles had the potential to significantly disrupt experiments and animals in the research building, in addition to potential cosmetic damage to residential buildings close to the pile locations.

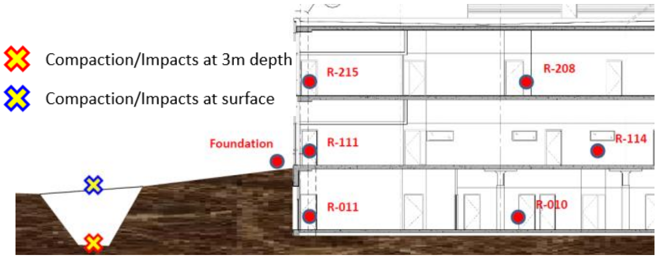

**Figure 1**: Building section showing relative vibration monitor locations during excavator testing.

Vibration measurements on the ground surface were also conducted using 6 monitors spaced out to 100 m with both impacts and vibratory compaction measurements at the ground surface and at a depth of approximately 3 m.

To accurately evaluate the risk of the pile driving activity it was determined that test piles on site would be required. Two test piles were installed using a 7,000 lb hammer at varying drop heights increasing from 5 ft to 20 ft. Vibration monitors were installed on the ground surface near the piling rig, within the research facility and hospital, and at the foundations of surrounding residential buildings.

Results from the Franki pile tests were then used to refine the construction vibration model developed with updated parameters related to large impact events.

## 3 Site vibration model

Results from the site tests were used to develop a model to evaluate vibration impacts from a range of construction equipment and activities. The model was defined as follows:

$$V_r = PPV_s\, D^{\alpha} + CL + \beta d$$

$V_r$ = predicted vibration level;
$PPV_s\, D^{\alpha}$ = transmission of vibrations in the ground;
$CL$ = attenuation by the building foundation; and,
$\beta d$ = transmission of vibration within the building.

Where:

$PPV_s$ = construction equipment source vibration level;
$D$ = distance between equipment and building foundation;
$\alpha$ = ground vibration decay factor;
$CL$ = foundation attenuation factor;
$\beta$ = structural floor decay factor; and,
$d$ = distance to interior space from foundation wall.

Inputs to the model were calculated from the measurement data. Plots of ground propagation and building

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transmission used to generate input parameters are provided in Figure 2 and 3, respectively.

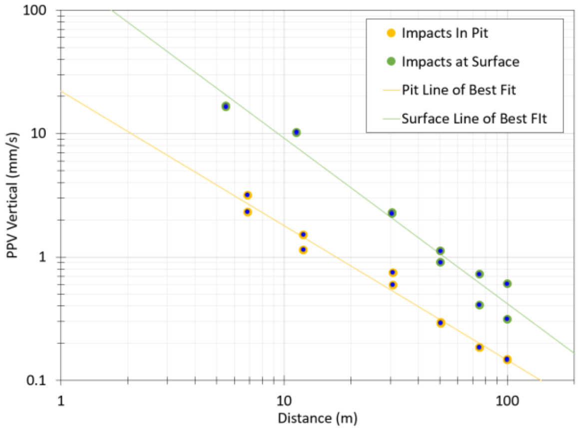

**Figure 2:** PVS ground propagation for excavator bucket impacts at surface and at depth of building foundations.

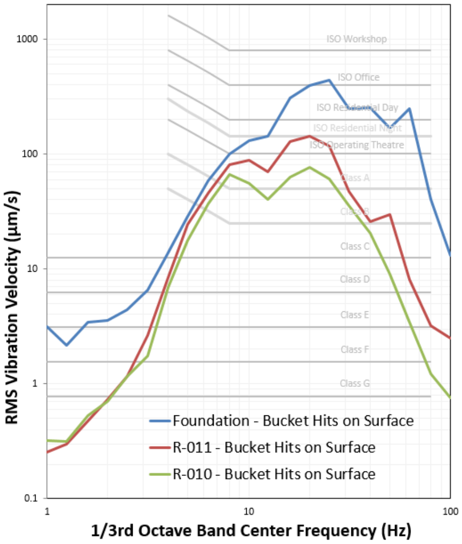

**Figure 3:** Vertical building transmission from excavator bucket hits at ground surface. See Figure 1 for measurement locations.

The model also includes vibration source type (impact vs. steady-state) and source vibration frequency. Permissible set-backs could then be calculated for each type of equipment and operating parameters.

## 4 Design criteria and verification

Construction impacts to be addressed included:

- disturbance to research animals and biological experiments;
- operation of sensitive equipment (e.g. microscopy);
- occupant comfort; and,
- cosmetic structural damage.

Specific criteria were developed for each of these receivers to ensure adequate protection of all assets. A summary of the generic vibration criteria selected is included in Table 1 for reference [1, 2].

**Table 1:** Selected vibration criteria.

| Receiver | Criteria | Vibration Level (RMS) | Basis |
|---|---|---|---|
| Research Facility | Max | **ISO-Operating Theatre**<br>0.1 mm/s | Protection of animals |
| | Preferred | **Class-B**<br>0.025 mm/s | Operation of equipment |
| Residences | Max | 25 mm/s | Cosmetic damage |
| | Preferred | **ISO-Residential Day**<br>0.2 mm/s | Human comfort |
| Existing Hospital | Max | **ISO- Residential Night**<br>0.140 mm/s | Patient comfort |
| | Preferred | **Class-B**<br>0.025 mm/s | Operation of equipment |

Protection of animals in the research facility was deemed the most critical and governed set-back recommendations. As such, verifying these criteria were appropriately selected was important to ensure the restrictions placed on the construction equipment were not overly restrictive.

During Franki pile testing vibration monitors within the animal research areas recorded a peak vibration velocity of 0.75 mm/s which corresponded to an RMS velocity of 0.1 mm/s. Spectrally these measurements were in agreement with the ISO-Operating Theatre criteria selected for the animal research areas. During tests staff within the animal research areas did not perceive any vibration impacts and all activities were conducted uninterrupted including surgery.

## 5 Vibration control during construction

While the construction vibration model did include site specific parameters and was verified by on site testing and measurements, a vibration monitoring protocol was required to guide the construction team in the protection of critical assets. Safe operating set-backs were provided as a general recommendation; however, these requirements may not be followed on site and cannot completely cover all possible activities and pieces of equipment.

To provide the required level of protection a vibration monitoring protocol was developed which focussed on the research facility and animal protection. This included monitor locations, alarm and trigger levels to change work, and stop-work conditions.

Over the course of the demolition and construction activities measurements collected were continually analyzed to verify the vibration model and make any updates to refine control requirements as appropriate.

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# ABSTRACTS FOR PRESENTATIONS WITHOUT PROCEEDINGS PAPER
# RÉSUMÉS DES COMMUNICATIONS SANS ARTICLE

## Relationship Between Railway Ground-Borne Vibration Propagation And Track Elevation – A Field Study

*Adam Collins*

Railway corridors form vital transportation routes for moving goods and people across Canada. These routes have seen explosive growth of close proximity residential developments in Canada's major cities and the impacts due to rail traffic on residences is a growing concern. A relationship between railway ground-borne vibration propagation and track elevation relative to points of reception was investigated and proposed based a field study of vibration measurements taken adjacent to railway corridors in Ontario and Alberta. The purpose of this study was to compare vibration measurements under three conditions: track elevated on berm, track at grade and track below grade, relative to points of reception. Other railway variables such as track condition, train speed and soil conditions were noted however were not assessed for this paper. Results of this study indicate track elevation is a factor in railway ground-borne vibration propagation. The importance of this relationship on land-use planning adjacent to railway corridors is discussed and existing guidelines for ground-borne vibration and vibration induced noise are summarized.

## Effects Of Cable Connections On Vibration Measurements

*Al D. Lightstone, Sam Du*

During periodic checking of vibration transducers with a shaker table, using sinusoidal excitation, it was noticed that the waveforms produced by the transducers at low frequencies showed significant distortion. It appears that this is due to unintended forces on the transducer due to the signal cable. One of the ramifications is that the measured low frequency spectrum will potentially contain artifacts that are not directly due to the vibration input. Empirical results are presented of a mini-study of the effects on transducer signal output of different types of signal cable and cable dressing.

Case Study

armtec
VISION | BUILT

# HERB GRAY PARKWAY

Armtec recently completed a milestone project, constructing a total of nineteen sound barrier walls along an 11 km stretch of Canada's busiest gateway, the Detroit-Windsor border highway. The Windsor highway, better known as the Herb Gray Parkway, was a multibillion-dollar project that was five years in duration to completion, making it the largest highway infrastructure project in Ontario's history.

The highway is intended to provide a freeway for commercial drivers and reduce heavy traffic in residential areas. Not only was the overall design purpose to alleviate urban traffic, incorporating community and green benefits to promote healthy living within communities was a major highlight to the project. The vision of creating a green corridor would support recreational trails, green space and protected natural areas to protect communities from the freeway. Extensive environmental studies and measures were conducted.

Armtec supplied a total of nineteen noise barrier walls that included ground-mounted and structure mounted designs.

An interesting aspect of this project is the integration of multiple of Armtec's product lines. The wall features custom "ledge stone" patterned absorptive Durisol panels, ACRYLITE® Soundstop transparent panels, and an ACRYLITE Soundstop TL-4 system.

With many efforts of value engineering and collaboration to capture the architects envision, Armtec succeeded in providing a viable solution, as well as meeting both client and owner's expectations.

**OWNER**
MTO

**CONTRACTOR**
Parkway Infrastructure Contractors (PIC)

**INSTALLATION CONTRACTOR**
Base Tech General Contracting Inc.
McKelvey Contracting

**LOCATION**
Windsor, Ontario

CUSTOM LEDGE STONE PATTERNED DURISOL PANELS

DURISOL PANELS INTEGRATED WITH ACRYLITE SOUNDSTOP

STRUCTURE-MOUNTED TL-4 SYSTEM TRANSITIONING INTO GROUND-MOUNTED NOISE BARRIER

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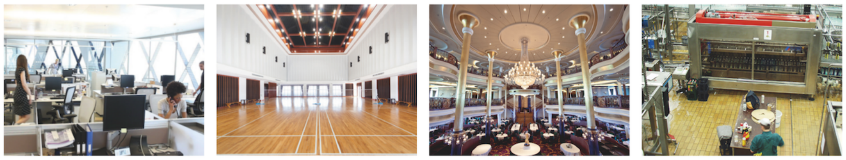

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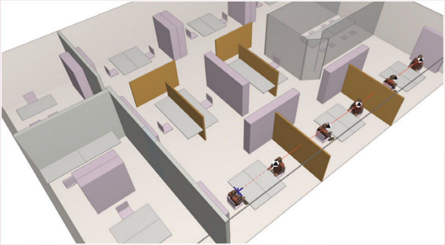

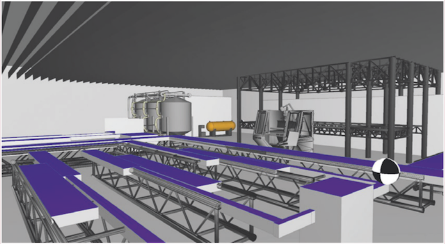

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# SPEECH SCIENCES AND COMMUNICATION - SCIENCES DE LA PAROLE ET COMMUNICATION

# VOICES IN NOISE OR NOISY VOICES: EFFECTS ON TASK PERFORMANCE AND APPRECIATION

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## 1 Introduction

Processing information that is presented orally in background noise requires focusing on the target signals while suppressing the irrelevant sounds. Whether this can be done successfully depends on a complex interplay between features of signal and noise tasks at hand, and individual characteristics of the listener [1],[2],[3].

Irrelevant speech is often shown to be particularly disturbing, especially when it is intelligible and meaningful. More generally, phonological similarity between target and masking signal might also increase the influence of the masker [1].

Voice disorders can be regarded as a particular type of noise because 3the noise is actually part of the target signal. Dysphonia is defined as a speech disorder 'characterized by the abnormal production and/or absences of vocal quality, pitch, loudness, resonance, and/or duration, which is inappropriate for an individual's age and/or sex.' (ASHA). The effect of dysphonia on learning is a very pertinent question, as dysphonia is often reported in teachers.

Dysphonic voices (DV) have been shown to affect information processing and language comprehension in children [4] as well as in adults [5]. This is in line with the generally known effects of irrelevant noise on task performance. It is less clear how important the effects of DV are, compared to other external noise sources.

No relationship has been found between the severity of the dysphonic voice and the degree of decrease in information processing [6]. It remains to be seen whether voice disorders yielding a creaky versus a breathy voice have different effects on information processing.

Finally, it has been little investigated how dysphonic noise and background noise might interact, and what their combined effect on information processing is. Again, this is a pertinent question as dysphonic teachers teaches in some kind of (classroom) background noise.

In this work, the effect on information processing is investigated for (1) DV versus multitalker babble background noise, and versus non-speech background noise with a spectrum similar to dysphonic noise, for (2) voice disorders with different perceptual characteristics, and for (3) the combined effect of DV and multitalker babble. Information processing is studied in two ways, by looking at the retention of information, measured with an exam, and by looking at subjectively reported ease of processing.

## 2 Method

### 2.1 Participants and protocol

Forty-nine volunteers between 18 and 30 years old (average: 21.1 years) participated. Participants were instructed to listen carefully to 10 different 5 minute lectures on various topics. After each lecture, they had to write down up-to five key elements they had retained from the lecture, as well as answer six true/false questions. After all lectures had been listened to, participants were asked to order them in terms of how easy it was to follow the content of the lecture, with the easiest first and the hardest at the last place.

### 2.2 Listening conditions

All lectures were read by a 40-year female speech therapist. Play-back of the lectures was done with different voice characteristics and different fragments of background noise.

For the voice characteristics, three different DV were simulated using the software TC Helicon VoiceOne. A panel of three voice experts and five non-expert listeners judged the voice quality of the simulations. The selected simulations were judged as clearly dysphonic and could not be distinguished from natural (non-simulated) voices by the non-expert listeners. One healthy voice condition was added to the three simulated DV, so in total four different voice conditions were included.

Background noise conditions also varied. All four voice conditions were presented twice, once without additional background noise and once with unintelligible multitalker babble noise.

Finally, two different background noise conditions were added for the healthy voice only. So-called dysphonic background noise was created from the spectrum of one particular dysphonic voice fragment by randomizing the phase. The dysphonic voice was mixed with the healthy voice with two different angles of incidence. Once the healthy voice was played to the right ear and the dysphonic noise to the left ear, in the second condition both speech and noise were played to both ears.

Participants listened to the lectures through headphones, voices were played at 68 dB calibrated with the Head And Torso Simular (HATS) type 4128C from Brüel & Kjær. Multitalker babble and dysphonic noise were played at 63 dB.

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# 3 Results

## 3.1 Task performance

Participants performed quite well on the information processing task. On average 4.2 key elements (maximal score 5) were correctly reproduced, with an interquartile range spanning from 3.5 (first quartile) to 5 (third quartile). Similar results were found for the true/false questions, on average 3.9 of the six questions were correctly answered, ranging from 3.0 (first quartile) to 5.0 (third quartile).

Mixed linear regression analyses revealed no significant effect of voice condition, background noise, or the interaction of voice and noise on the scores of the open questions and the true/false questions, with all p-values clearly exceeding 0.1.

## 3.2 Subjective rating

Mixed model linear regression showed a clearly significant interaction effect of voice condition and background noise on reported ease to process information ($p<0.0001$). This results is investigated further by pairwise Tukey post-hoc testing ($\alpha=0.05$).

The clearest effect is seen for multitalker babble, these conditions are rated significantly worse compared to conditions without additional background noise, for all voice conditions.

Dysphonic noise is rated significantly less positively compared to the healthy voice without additional background noise, regardless of the angle of incidence of the dysphonic noise. Compared to a healthy voice in multitalker babble, especially the condition with dysphonic noise presented to both ears scored significantly less disturbing. When the dysphonic noise was presented to the left ear only, scores are closer to the multitalker babble, the difference being no longer clearly significant ($0.05<p<0.1$).

The effect of DV appears to be similar to the dysphonic noise; DV are also rated significantly less favorably compared to the healthy voice without background noise. Compared to the healthy voice in multitalker babble, they are rated significantly easier. No significant differences are seen in-between the different DV, nor between DV and dysphonic noise.

DV presented in multitalker babble do not appear to additionally lower the subjective rating; in multitalker babble no significant difference is found for scores of the healthy voice in multitalker babble compared to the DV.

# 4 Discussion

Task performance appears to be relatively unaffected by the DV and the background noise. For the background noise, this could be partially explained by clearly positive signal-to-noise ratio (5 dB) and the moderate level of the background noise. The dysphonic disorders were not extreme either. In addition, for a complex task such as information processing from a full text, it has been shown that contextual information and higher level of concentration required might actually be beneficial to deal with background noise [7],[8].

For the subjective rating, both multitalker babble and DV are rated less favorably compared to a healthy voice without additional background noise. Speech sounds (multitalker babble) are known to be likely to draw the listener's attention, whereas the dysphonic sounds might be difficult to separate perceptually from the target signal as it is inherently part of it. In this experiment, the multitalker babble has clearly been recognized more strongly as an interfering noise source. The dysphonic characteristics have also negatively influenced the rating. The fact that they are produced by the speaker, hence inherently connected to the target signal, appears to be less important, as adding dysphonic noise as background noise to a healthy voice leads to similar results.

# 5 Conclusions

The reported difficulty to process orally presented information clearly increased when lectures are presented in multitalker babble. DV have also a negative, albeit less strong, effect. Different DV do not appear to lead to distinguishable effects, and within background noise, DV do not lead to further increase in reported difficulty compared to the healthy voice.

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# THE ROLE OF INHIBITION IN OLDER AND YOUNGER ADULTS' LEXICAL COMPETITION

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## 1 Introduction

With age, uncertainty becomes more pronounced in speech perception; it becomes harder to recognize words in noise [1] and to inhibit similar sounding high-frequency lexical competitors [2]. Similar to [3], we contrast lexical competition and speech perception, but in older and younger adults, because older adults have weaker encoding of some phonetic contrasts [4, 5] and greater lexical effects than younger adults [2, 6]. The lexical bias found in older adults [6] could be indicative of decreased lexical inhibition, which would result in increased activation among lexical competitors. Indeed, [7] found that older adults had greater difficulty than younger adults recognizing words with many semantic neighbours, suggesting that older adults exhibit difficulty inhibiting competitors.

We manipulated voice onset time (VOT) and present a phonological competitor to the target word to investigate the role of phonetic sensitivity and lexical competition in resolving spoken word recognition. To investigate the influence of domain-general inhibition in resolving lexical competition, all participants completed a Simon task [8]. Given the previous lexical and inhibitory results, we expected older adults to have more difficulty inhibiting lexical competitors, especially as speech becomes increasingly ambiguous.

## 2 Method

### 2.1 Participants

All younger (n=27, $M_{age}$=21.6) and older adult (n=27, $M_{age}$=68.1) participants underwent an audiological screening and none had a Pure Tone Average (PTA) threshold of greater than 25 dB HL. All participants were native speakers of English, although some had beginner to intermediate knowledge of a second language.

### 2.2 Stimuli

A female native speaker of English recorded the target minimal pairs and distractor items in a carrier sentence in a sound-attenuated booth. There were six /p/-/b/ minimal pairs (peach-beach, pear-bear, pin-bin, etc.). We also included an equal number of /ʃ/- and /l/- initial distractors. We manipulated VOT by cross-splicing to create a 9-step continuum for each minimal pair.

### 2.3 Procedure

Participants were seated in a sound-attenuated booth approximately 550 mm away from the display screen. Our eyetracking task used a four-picture visual world paradigm. Each display included a /p/-/b/ minimal pair, one /ʃ/- and one /l/-initial image. Each target stimulus was presented 10 times, with an equal number of distractor trials (/l/ or /ʃ/ initial target) for a total of 1080 trials (6 minimal pairs x 9 steps x 10 repetitions = 540 test trials + 540 distractor trials). Each trial began with a 500 ms preview of the display. Participants were instructed to click on the image that best matched the word played over headphones. Participants completed the first half of the eyetracking task, followed by the Simon task, and then the second half of the eyetracking task. Our Simon task [8] was comprised of 40 congruent, 40 incongruent, and 40 neutral trials (120 trials total). Participants were presented with a coloured circle (blue or red) on a screen and asked to respond with one of two keys on a keyboard depending on the colour of the circle (left Shift key-red circle, right Shift key-blue circle). Congruent trials presented the coloured circle on the side of the screen corresponding to its response side (e.g., blue circle on the right side), while incongruent trials presented the coloured circle on the opposing side (e.g., blue circle on the left side). Neutral trials presented the circle in the center of the screen. The session took approximately two hours.

## 3 Results

### 3.1 Data processing and analysis

We calculated the proportion fixation to each image for the 2000 ms following the stimulus word onset, and then calculated a discrimination score as the difference between looks to the target image and looks to the competitor [9]. Thus, a discrimination score approaching one indicates almost all looks were to the target, while a score close to zero indicates participants looked about equally to both. Following [3], we fit a series of logistic regressions to the mouse click responses to find the category boundary for each participant and continuum. These category boundaries were used to set the 'correct' response for each auditory stimulus and to standardized the continuum steps (Relative continuum step) such that the category boundary was set to zero for each participant and continuum. Only trials where the correct image was selected were included in our analysis. We ran a mixed-effects linear regression on discrimination score with Relative continuum step, Age group, and Simon score as predictors. Simon score was calculated as the average difference between response time

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in incongruent and neutral trials, thus a higher Simon score corresponds to poorer inhibitory skill. To include both sides of the continuum in one model, we used absolute distance from the category boundary. Age group and Simon score were rescaled and centered on zero.

### 3.2 Model results

Table 1 presents the results from our mixed-effects linear regression. As expected, we find that tokens from the clear end of the continua are easier to discriminate than those near a category boundary (β=0.11, t=10.35, p<0.001), and that younger adults are better at discriminating regardless of the ambiguity of the token (Figure 1A; β=0.04, t=2.23, p=0.03). We find a main effect of Simon score (β=0.07, t=2.02, p=0.06), suggesting that those with poorer inhibition show better discrimination. This is qualified, however, by a two-way interaction involving Simon score. We find that younger adults with poorer inhibition discriminate better than those with better inhibition (Figure 1B; Age Group x Simon score: β=0.12, t=2.13, p=0.04).

**Table 1:** Fixed effects estimates from mixed-effects linear regression of discrimination score.

| Fixed Effect | β Estimate | Std. Error | t Value | p | |
|---|---|---|---|---|---|
| Intercept | 0.53 | 0.02 | 26.93 | <0.001 | *** |
| Continuum step | 0.11 | 0.01 | 10.35 | <0.001 | *** |
| Age group | 0.04 | 0.02 | 2.23 | 0.03 | * |
| Simon score | 0.07 | 0.03 | 2.02 | 0.05 | * |
| Con. step x Age group | -0.003 | 0.02 | -0.16 | 0.88 | |
| Con. step x Simon score | 0.02 | 0.03 | 0.86 | 0.39 | |
| Age group x Simon score | 0.14 | 0.07 | 2.19 | 0.03 | * |
| Con. step x Age gr. x Simon | 0.08 | 0.06 | 1.35 | 0.18 | |

## 4 Discussion

We find that, overall, younger adults are better at discriminating targets from competitors, especially younger adults with poorer inhibitory skill. We suspect that these younger adults are not distracted by poor competitors (i.e., when targets are clear and far from the category boundary), but are especially distracted by strong competitors (when targets are close to the category boundary). This is supported by the direction of the non-significant trend between Continuum step, Age group, and Simon score.

Despite our initial predictions, we found no strong relationship between inhibition and discriminatory ability in the older adults. This could be because we have a relatively strong group of older adults who mostly are performing close to the mean (see Older Adult panel of Figure 1B). We may also have found different results if we had chosen a linguistic measure of inhibition, rather than the domain-general Simon task. We do find that older adults have more difficulty discriminating targets from competitors, regardless of the clarity of the stimuli, which suggests older adults do have more difficulty inhibiting lexical competitors compared to younger adults. This behaviour, however, is not predicted by our measure of inhibitory ability.

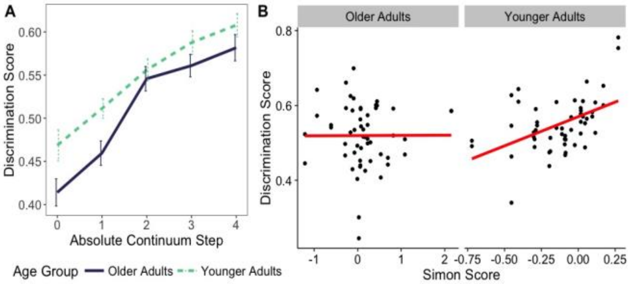

**Figure 1:** Discrimination score (proportion targets looks – proportion competitor looks) by (A) age group and absolute relative continuum step, and (B) age group and simon score.

## 5 Conclusion

Our results provide evidence that older and younger adults employ different strategies when resolving lexical competition, as evidenced by the different role played by inhibitory ability across the two age groups.

## Acknowledgments

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# SENSORY INTEGRATION FROM AN IMPOSSIBLE SOURCE: PERCEIVING SIMULATED FACES

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## 1 Introduction

Recent research has shown that aero-tactile cues influence speech perception even without the presence of an acoustic signal [1]); when participants viewed a silent bilabial articulation that co-occurred with a puff of air felt on the skin, they were significantly more likely to perceive it as aspirated. These results and others [2] suggest that this integration is relatively automatic, enough so that it occurs in the absence of an interlocutor who could be the airflow source. However, it may be that perceivers are willing to extend physical capabilities to these non-present sources because they are human and therefore possible sources of the aero-tactile cue.

The results from [1] established that participants integrate aero-tactile information that is presented alongside videos of real people. The current study examines whether aero-tactile information presented synchronously with visual speech information from an impossible source – a computer-animated face on a computer monitor – can affect perception of consonants. Unlike a human, a computer's means of producing sound should not be expected to produce a puff of air in the real world. However, we predict that artificial air flow will be perceived as speech aspiration when paired with a computer-generated avatar. Based on the findings in [1], we predict that participants will demonstrate a baseline /ba/ bias in trials without airflow. Evidence of integration from an impossible source would support the idea that visual-tactile integration is an automatic process that occurs even in the absence of an interlocutor capable of producing the stimuli.

## 2 Method

11 Native English speakers were recruited from the University of British Columbia Linguistics Department subject pool and were compensated $5 for a thirty-minute session. All participants reported no speech or hearing disorders. Participants were seated in a sound booth in a high-backed chair and were instructed to keep their back against the chair as much as possible during the study. They were shown an animated video of a computer-animated head producing a bilabial plosive while listening to multi-talker babble noise through headphones. Some of the presentations were accompanied by a light, synchronous puff of air on the neck. Participants were asked to indicate what syllable they thought the avatar had produced (i.e., pa or ba) using the keyboard.Response keys were counterbalanced across participants.

**Figure 1**: Computer generated avatar used in the study thought the avatar had produced (i.e., pa or ba) using the keyboard. Response keys were counterbalanced across participants.

A two-dimensional female avatar (see Figure 1) was created using computer software (CrazyTalk 8). A single video clip was then made of the avatar producing a bilabial plosive. An accompanying sound file was created using the software's TTS feature and the avatar's stop closure and release were synchronized with the closure and burst in the waveform. The clip was then exported to a QuickTime file. This initial clip was used for the trials that did not have accompanying airflow. To create the video clip for the puff condition, the audio was extracted from the video clip and a 50 ms 10 kHz sine wave was inserted in the left channel. To account for system latency, the tone was placed 35 ms earlier than the stop burst. This ensured that the visible release of the bilabial closure and the release of the airflow from the tube would be synchronous. The left channel of the sound file was then extracted and recombined with the QuickTime file to create a silent video clip that would trigger a synchronous air puff.

The puff was created using a California Air Tools 4610 air compressor connected to a switchbox via a ¼ inch diameter vinyl tube all located outside the sound booth. A second ¼ inch vinyl tube passed from the switch box through the access port of the sound booth and was attached to a flexible boom arm fitted to a microphone stand. The open end of the tube was positioned ~7 cm in front of the participant's suprasternal notch. Using Direct Sound EX-29

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headphones, participants listened to a babble track played from a separate computer located outside the sound booth. The experiment was run using PsychoPy [3] on an iMac computer directly in front of the participant.

## 3 Results

Statistical analysis employed a Generalized Additive Mixed- Effects Model in R [4], following the formula:

$$Response \sim Condition + s(Trial\ Number, Participant, bs = "fs", m = 1)$$

Where *Response* is coded 0 for /ba/ and 1 for /pa/, *Trial Number* is the ordered position of the individual token presentation in time, and *Condition* is “puff” or “no puff”. The first term *Condition* is the fixed term. The second term *s(Trial Number, Participant, bs = “fs”, m = 1)* is the random effect of trial order by participant. The fixed term (*Condition*) is significant (z-value 2.01, $p = 0.044$. The random effect of trial order is highly significant (Chi Sq = 141.8, $p < 0.001$). In the puff condition, participants responded /pa/ in 76% (SE = 0.06) of the trials. In contrast, when there was no puff, participants reported seeing /pa/ 34% (SE = 0.08) of the time. The results have an adjusted R-squared of 0.974, accounting for 95.6% of the deviance. Almost all variance is accounted for by the effect of trial order, as seen in Figure 2. The results show that participants mostly answered that they perceived /ba/ at the beginning of the experiment, yet during the experiment they eventually all reported perceiving /pa/. In the initial state, the bias toward /b/ is below -4. There is a second phase, where the propensity to answer /p/ rapidly increases the change of state. In the final state, the bias remains above 4. This sequence of events occurred for all participants. The start of the state change varied considerably between participants although the slope of change was very similar.

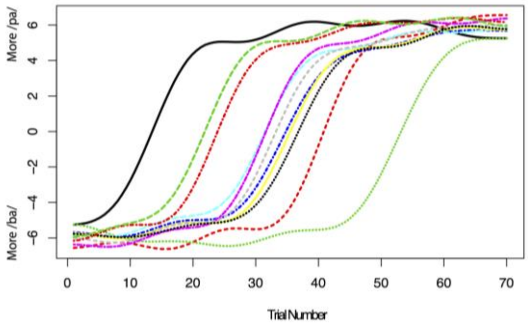

**Figure 2**: Effects of trial order on participant answer.

## 4 Discussion and conclusions

The current study tested the hypothesis that perceivers can integrate aero-tactile speech information from an impossible source. It was predicted that participants would provide more /pa/ responses when they are presented with both visual and aero-tactile stimuli than when presented with only the visual stimulus. Condition emerged as a significant factor such that participants reported significantly more /pa/ responses during trials in which they felt synchronous airflow. However, Condition effect is overshadowed by the large effect of Trial Number. As evidenced in Figure 2, participants began the task with a /ba/ bias unrelated to Condition. By the second half of the experiment, however, they exhibit a /pa/ bias. This result is markedly different from the response biases found in [1]. There, the authors reported a /ba/ bias in the Visual-only condition and found no effect of trial order on response. This suggests that while participants in the current study were indeed integrating the aero-tactile speech information from a computer-generated source, they did so differently from participants in [1], who observed real-life productions of the syllables.

One possible explanation is that the effect of trial order is related to the nature of the visual stimulus. Participants were presented with a single visual token, a fact they appear to have noticed. They initially experienced this articulation as a /ba/, reflecting the expected bias [1]. Then, as they experienced more trials that included airflow (which felt more /pa/-like), they may have begun assuming that this single articulation was /pa/. Thus, the aero-tactile stimulus appears to have caused them to associate the video of the avatar with a /p/ rather than a /b/, so that they effectively learned the articulation was a /p/.

While /b/ and /p/ have traditionally been considered a single viseme [5] and thus visually indistinguishable, our findings support those of [6] and [1], whose work suggest a visual distinction between the two sounds. If /b/ and /p/ were in fact visually identical articulations, we would predict a replication of the findings in [1]. Instead, our findings support the idea that there are subtle visual differences between the two articulations that perceivers are sensitive enough to detect. This study showed that aero-tactile stimuli alone was sufficient to cause participants to associate the simulated face video with /p/ within seventy trials. Experience alone is sufficient to train listeners to distinguish these “sounds”.

## Acknowledgments

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# ACOUSTIC ANALYSIS OF EMOTIONAL SPEECH PROCESSED BY HEARING AIDS

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## 1 Introduction

The speech signal carries important information about the emotional state of the talker. Listeners with hearing loss experience difficulties identifying vocal emotion, possibly due to threshold hearing loss [1] and/or changes in supra-threshold auditory or cognition processing [2]. Some evidence shows that current generation hearing aids do not work well for improving vocal emotion perception [3]. It is likely that the processing of speech sounds to increase audibility also changes the acoustic cues used for emotion perception, including amplitude and spectral cues [4, 5]. Increasing the gain for low-level sounds more than the gain for high-level sounds makes the amplitude envelope of speech less variable. Increasing the amount of high-frequency energy to meet hearing aid fitting targets changes the spectral characteristics of speech. One study found that listeners with hearing aids are in fact more sensitive to intensity cues than normal-hearing listeners on an arousal rating task [6]. Comparing the effects of different types of simulated hearing aid processing on vocal emotional cues may inform us on how current hearing aids affect emotion perception by listeners with hearing loss.

## 2 Method

### 2.1 Original speech materials

There were 140 sound files selected from the recordings of the younger female talker in the Toronto Emotional Speech Set [7]. These sound files consisted of 20 different sentences, each spoken in 7 emotion conditions: Angry, disgust, fear, happy, neutral, pleasant surprise and sad. Sentences consisted of the carrier phrase *Say the word* followed by a monosyllabic keyword.

### 2.2 Hearing aid processing conditions

In the Unaided condition, the recordings were processed to simulate the signal received by a listener with sloping bilateral hearing loss (a pure-tone average of 46.25 dB HL at 0.5, 1, 2 and 4 kHz). In three additional conditions corresponding to three types of hearing aid processing, the recordings were processed using a Phonak hearing aid simulator according to NAL-NL2 targets [8] for the same hearing loss simulated in the Unaided condition.

In the Linear condition, the same amount of gain was applied regardless of the sound input level. In Slow Compression and Fast Compression, there was more gain applied for low-intensity than high-intensity sounds, with a compression ratio ranging from 1.1 at lower frequencies to 2.9 at higher frequencies. The speed of compression was about twice as fast in Fast Compression as in Slow Compression. The processed speech was played at 70 dB $SPL_A$ from a loudspeaker in a sound-attenuating booth, and speech was recorded using microphones in the ear canals of a mannequin. All other hearing aid features (directional processing, SoundRecover, etc.) were disabled.

### 2.3 Acoustical analysis

Since duration and $F_0$ are not expected to be affected by these processing conditions, only the following measures were taken using the Praat speech analysis program [9]: mean intensity, intensity standard deviation (Intensity SD), and spectral centre-of-gravity (Spectral CoG).

### 2.4 Statistical analysis

For each acoustic measure, the effects of processing conditions were compared using pairwise *t*-tests with Holm correction. To examine whether emotion conditions were affected differently by processing conditions, an analysis of variance was conducted for Intensity SD and Spectral CoG, with Processing Condition and Emotion as within-subject factors. Significant interactions were analyzed by comparing Emotion conditions within each Processing Condition.

## 3 Results

### 3.1 Effects of hearing aid processing on speech acoustic measures

Mean intensity differed across all processing conditions ($p$'s $< 0.001$), with the lowest overall intensity in the Unaided condition, followed by Fast Compression, Slow Compression and Linear (+3, +8, and +9 dB relative to Unaided, respectively). Intensity SD also differed across processing conditions ($p$'s $< 0.001$), with the greatest intensity variation in Linear and the least variation in Fast Compression (Figure 1).

Spectral CoG differed across all processing conditions ($p$'s $< 0.01$), with Fast Compression having the highest Spectral CoG and Unaided having the lowest Spectral CoG (Figure 2).

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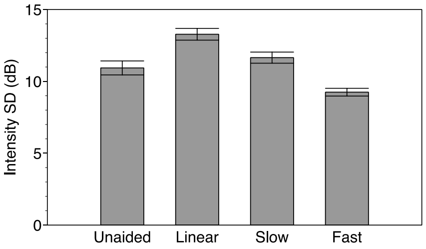

**Figure 1:** Intensity SD across processing conditions.

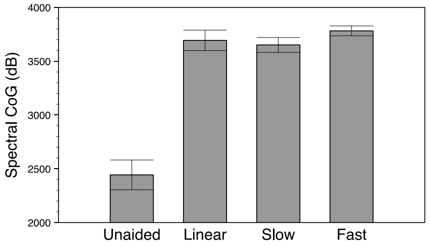

**Figure 2:** Spectral CoG across processing conditions.

### 3.2 Interaction of hearing aid processing with emotion condition

There was a main effect of Processing Condition on Intensity SD, $F_{(3,\ 57)} = 396.3$, $p < 0.001$, a main effect of Emotion, $F_{(6,\ 114)} = 47.09$, $p < 0.001$, and an interaction of Processing Condition with Emotion, $F_{(18,\ 342)} = 36.6$, $p < 0.001$. Emotion conditions with the largest intensity variation in the Unaided condition (Angry, Happy) were disproportionately affected by amplitude compression (Figure 3). Some pairs of emotions were no longer distinguishable, e.g., Angry and Disgust were significantly different in the Unaided condition ($p < 0.001$), but not in the Fast Compression condition ($p = 0.54$).

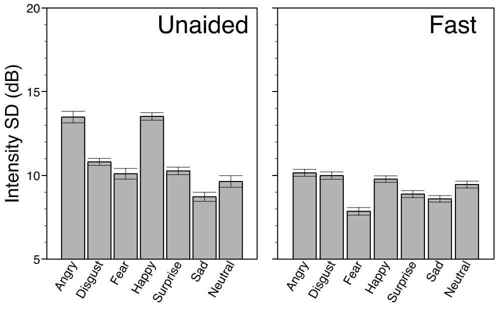

**Figure 3:** Intensity SD across emotion conditions, in the unaided and fast compression conditions.

There was a main effect of Processing Condition on Spectral CoG, $F_{(3,\ 57)} = 454$, $p < 0.001$, a main effect of Emotion, $F_{(6,\ 114)} = 26.23$, $p < 0.001$, and an interaction of Processing Condition with Emotion, $F_{(18,\ 342)} = 68.14$, $p < 0.001$. The emotion condition with the lowest CoG in the Unaided condition (Sad) became the condition with the highest Spectral CoG in Fast Compression (Figure 4). The emotion condition with a higher CoG than any other emotion condition in the Unaided condition (Angry) became very similar to other emotion conditions in Fast Compression.

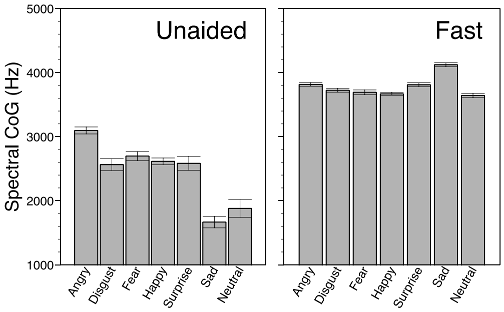

**Figure 4:** Spectral CoG across emotion conditions, in the unaided and fast compression conditions.

## 4 Discussion

In this study, simulated hearing aid processing affected two acoustic cues used in emotion perception, namely, intensity variation and spectral cues. The effects of hearing aid processing varied according to the type of vocal emotion. In some cases, hearing aid processing led to emotions being less distinguishable on these two acoustic cues. Future directions may include testing listeners with normal hearing and hearing loss on these processed recordings to determine how changes in specific acoustic cues affect emotion perception.

## Acknowledgments

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# INDIE-POP VOICE: HOW A PHARYNGEAL/ RETRACTED ARTICULATORY SETTING MAY BE DRIVING A NEW SINGING STYLE

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## 1 Introduction

Different genres of singing may be characterized in part by singers' articulatory settings [1]. Bateman [1], for example, notes that pop singing is often characterized by horizontal expansion and vertical compression of the lips, while jazz singers tend to use labial protrusion. The articulatory settings associated with a given singing style are known to have noticeable, systemic effects on the acoustics of the singer's pronunciation [2].

Recently, a new singing quality has emerged. Initial popular descriptions have sometimes called this quality "indie-pop voice" [3], and have focused on unusual vowel pronunciations and characteristic front-rising diphthongs. Our study investigates the possibility that indie-pop singers use a pharyngealized articulatory setting that may be motivating other vowel changes. As a precursor to the present experiment, we impressionistically evaluated the sounds of indie-pop, including the front-rising diphthongs and the contexts in which they appear, the overall vowel qualities, as well as certain consonant sounds, especially /r/. Careful observation suggests that, while the details and degree of these characteristics vary from artist to artist, they have a few important features in common.

First, we found that front-rising diphthongs can occur after any vowel except /i/, /ɪ/, or /u/, and most occur before coronal consonants. We took this to suggest that the diphthongs are prolonged audible transitions between the tongue's vocalic position and the articulatory target for the following consonant. Second, we observed a pervasive pharyngeal sound. Reinforcing this, we observed that, in some artists, /r/ sounds were realized postvocalically as high-front vowels, which could indicate that the pharyngeal component of /r/ was not distinctive in that environment. Pharyngeal constriction can be achieved via various articulations [4], but we interpreted these initial observations as consistent with retraction of the tongue body. In addition to reducing pharyngeal volume, this could also prolong the transitions between vowels and coronal consonants, simply by increasing the physical distance the tongue must travel.

To investigate the articulatory setting used in the indie-pop singing style, we conducted an acoustic study of several different artists, comparing the vowel formant values of sung vowels in indie-pop songs to the same vowels in spoken interviews produced by the same artists. We expect to see that, as compared to the interviews, vowels in indie-pop singing will exhibit higher F1 values, an acoustic correlate of pharyngeal constriction [5], and lower F2 values, a correlate of tongue dorsum retraction [6].

## 2 Method

The artists and songs were chosen based on the description of indie-pop voice in [3] (i.e., all have the characteristic diphthong). From an initial 9 artists, 4 were excluded for having native dialects from outside English-speaking North America. Interviews were chosen for clarity and ease of access. Songs and interviews on YouTube were recorded using peggo.tv, converted into .WAV format with Audacity 2.1.1, and spectral measurements were taken using Praat 5.4.19.

A subset of the English vowel inventory was analysed. No distinction was made between /ɑ/ and /ɒ/, nor between /ɔ/ (preceding /r/) and /o/. Diphthongs and schwas were excluded, as were any vowels that were too short to clearly distinguish from their environments. Spectral measurements were taken from either the first stable formant area of the vowel, or if there was none, from its approximate midpoint.

The measurements we took were as follows (listed as "vowel: number of samples from songs, number of samples from interviews"): i: 25, 18; ɪ: 21, 17; ɛ: 19, 19; æ: 21, 19; ɑ: 26, 26; o: 21, 13; u: 10, 15; ʊ: 9, 7; ʌ: 17, 22.

## 3 Results

In general, the sung vowels exhibit a qualitative trend of higher F1 compared to the spoken vowels, particularly in high and front vowels. We also observed lower F2 values, particularly in high vowels. These apparent patterns are absent in the low back vowels.

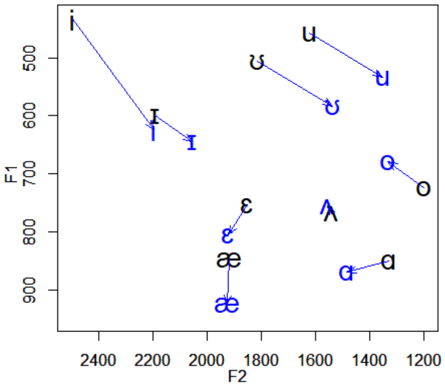

**Figure 1:** Average vowels in speech (black) and singing (blue)

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Performing ANOVAs of F1 by condition (sung; spoken) for each vowel, and another set of ANOVAs of F2 returned two significant results, both for the vowel /i/. The difference between the average spoken F1 and average sung F1 was significant (*p*=0.03), as was the difference between spoken and sung F2 (*p*=0.03). Additionally, for the vowel /ɑ/, the difference between spoken and sung F2 was nearly significant (*p*=0.051).

## 4 Discussion

Qualitatively, the pattern in Figure 1 aligns with our hypothesis. High and front vowels display an increase in F1 which can be attributed to pharyngeal constriction. The absence of this pattern in the low- and mid-back vowels is consistent with our hypothesis: these are the vowels whose constrictions are the farthest back in the mouth, so their inherent features are redundant with the proposed articulatory setting [4]. This can also explain why sung low vowels do not exhibit decreased F2: their features may be partially or entirely redundant with the articulatory setting of tongue retraction.

Similarly, it is noteworthy that the vowel which exhibited a significant difference between sung and spoken formant values was /i/. Its features are least redundant with our proposed articulatory setting, so the difference between sung and spoken /i/ should be the largest and easiest to detect. This may also shed light on indie-pop's characteristic diphthongs. Given that we found /i/ to be the most displaced vowel in indie-pop, and that indie-pop's diphthongs move toward the space which /i/ is leaving, it may be possible to apply a chain-shift model of sound change to indie-pop. This discussion, however, will be left for future study.

Another factor likely contributing to the weak *p*-values for vowels other than /i/ is variability between artists. There were insufficient measurements from each artist to perform individual statistical analyses, but this variability appears substantial. Some artists even show opposite patterns to those in Fig.1. For example, Shawn Mendes' sung high front vowels exhibit raised F2, despite his being qualitatively one of the strongest examples of indie-pop voice. This raises questions as to why artists with similar stylistic markings have different acoustic signatures. To address this, we draw analogy to sound change in spoken language.

In models of sound change, the initial stage might be more physiologically driven, but the resulting shift is later adopted as phonology [7]. Similarly, while indie-pop's distinctive diphthongs may originally have been a by-product of an articulatory setting, they have since been adopted as part of a musical style. For example, one online tutorial instructs the viewer to "add the letter i… after vowels" [8]. If the diphthongs are deliberately articulated, they can occur over a variety of articulatory settings and environments. Since there are many ways to reduce pharyngeal volume, a singer could even use a different articulatory setting despite exhibiting both pharyngealization and indie-pop's characteristic diphthongs. This poses difficulties for phonetic study as the presence of these diphthongs was the primary basis for an artist's inclusion.

A follow-up study should analyze more artists, and acquire enough data from each to compare them so as to construct a better picture of how the style is produced. It could also prove beneficial to include artists who do not prominently exhibit the front-rising diphthongs, but who bear other characteristics of the indie-pop style [3].

Finally, the present study relies exclusively on indirect measurements of articulation, which leaves room for alternative explanations of the acoustic results. With this in mind, future work may use ultrasound measurements of the tongue-root, ideally with professional artists, or possibly with trained phoneticians imitating indie-pop.

## 5 Conclusion

Acoustic analyses of five singers with an indie-pop style support the presence of an articulatory setting featuring pharyngeal constriction via tongue retraction. This may explain the style's characteristic diphthongs and vowel quality, though more robust data are needed. We also observed substantial variation between artists, possibly due to the stylistic adoption of diphthongs originally produced via an articulatory setting. Further research may use direct articulatory measurements and a larger sample size of both vowel measurements and artists.

## Acknowledgments

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# AN ACOUSTICIAN’S JOURNEY INTO HEARING AIDS

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## 1 Introduction

Scientific papers are not generally written in the first person. But, as the title suggests, this is a story about a personal journey so the author will beg the readers’ forgiveness if the writing lapses into I’s, my’s and me’s. Apologies in advance for a less technical, storytelling type of paper. I hope it might help someone.

There is a perception that an acoustician must have “golden ears”. That is, they are uniquely set with such superior auditory processing that the application of science is rendered superfluous. This perception persists in spite of the fact that it is at least two generations out of date. Creativity married to science is the answer these days. Still, it is an absolute anathema for an acoustician to wear hearing aids. It doesn’t look good. It’s alright for an artist or an architect to wear glasses. An acoustician should never don a pair of heating aids. But that’s exactly what I’ve done. I was fitted with hearing aids two years ago. I’m not supposed to be talking about this but I will. And I’m glad I have my hearing aids. I hope this story will encourage other acousticians to consider hearing aids, whether they know they need them or not.

## 2 The beginning of the journey

It’s difficult for someone seen as an expert in acoustics to admit that he or she has a hearing loss. I wouldn’t admit it for years.

But I am fortunate enough to have an audiologist as my wife. We met at ISVR in Southampton when we were doing our respective Masters’ degrees. Over the dinner table a few years ago she told me, judging by my increasing difficulties understanding conversation and the kind of mistakes I was making, that I probably had a hearing loss of 35 dB at 2000 Hz. When she finally measured my hearing it turns out she was spot on. 35 dB down at 2000 Hz. 35 dB is about the same Transmission Loss you would get from of a heavy and very well sealed door. 2000 Hz is the range of consonant frequencies that are critical for good speech discrimination. Phonemes like p, t and k are all clustered around this frequency. And so many words in English are defined by one differing phoneme – such as tin, pin and kin, for example. Three words easily confused if you can’t hear the phonemes. These high frequencies are the sounds that give words in Western languages their clarity. Stage actors, opera singers and, for that matter, the great Louis Armstrong all over-emphasise their consonants so they can be understood at the back of the room. Problem was, I couldn’t hear those consonants anymore. I was behind a heavy, well-sealed door.

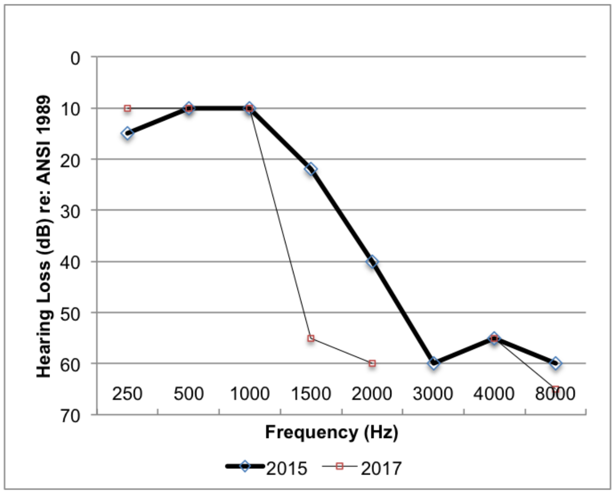

**Figure 1:** The author’s right ear audiograms showing the original 35 dB loss at 2000 Hz in 2015 and how it has progressed down to 1500 Hz in 2017.

## 3 The awakening

I was fitted with my hearing aids two years ago. The first few months were bliss. I could hear the world come alive again. I was warned that hearing aids would give me too much noise and that it would take a while to get used to it. It’s true; I could hear my middle age bones crackle too much. The floorboards in our hundred year old house made more noise than they used to. The sound of the wind in the trees that surround our house enthraled me. But none of this was noise. Here’s the thing, I design the sound in buildings, theatres and concert halls because I love sound. And if I can hear sound better in the most important building in my life – our home – that’s a good thing!

I could hear the consonants, at least for a while, but my speech discrimination was only slowly improving. My brain hadn’t had to figure those sounds out for a while. It’s something called neuro-plasticity. The brain is a bit like a muscle. If there are parts of it you’re not exercising, they fade away. But with new found exercise (i.e. my hearing aids) those parts of my brain will start to figure things out again. Initially my feeble brain couldn’t figure out all those k’s and t’s that I hadn’t really heard for so long. It was supposed to take about 6 months for neuro-plasticity to kick in. But it hasn’t really happened as planned.

## 4 The continuing journey

Copies of the author’s audiograms are shown in Figure 1. The first is from 2015 when I was first diagnosed and the

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second is from 2017. Only the right ear audiograms are shown for the sake of clarity. (The left ear is essentially the same as the right.) As mentioned, I have a 35 dB loss at 2000 Hz, that's shown in the 2015 audiogram. By 2017, that 35 dB loss had moved down in frequency to 1500 Hz. That's why I was continuing to have trouble with speech discrimination. My hearing aids have been adjusted accordingly so hopefully my neuro-plastic learning can start up again.

## 5 Comments and reflections

I'm a middle-aged man in a profession where I really shouldn't be seen wearing hearing aids – or writing about it for that matter. I don't really care.

There's something much more important than that. There is a stigma that still persists about wearing hearing aids and it extends to children. This is an area of study that I have become very much interested in because of my experience with hearing loss. Pittman has shown that a hard of hearing child needs to hear a word three times more frequently than a normally hearing child in order to understand that word and to incorporate it into his or her lexicon [1]. One study, in the early 1980s found that classroom noise alone accounted for 50% to 75% of the variance of reading delays of 1 year or more in elementary school students [2] – and that was for a normal hearing population. Too much reverberation in a classroom will impede speech. For the Hard of Hearing, this problem is exacerbated. ANSI recomends a maximum Reverberation Time of 0.6 to 0.7 seconds in classrooms. For the Hard of Hearing, Crandell has found that it should be shorter, in the range of 0.4 to 0.5 seconds [3]. Hearing aids and the early detection of their need can help address this.

Some parents with a hard of hearing child don't want to admit it. That's a mistake. And the child will pay for it. During elementary school they're effectively behind that heavy wooden door, standing outside in the corridor. It's pretty hard to hear the teacher that way. And in the early years – the most plastic of neuro-plasticity – they are still learning language. If they can't do that during the critical early learning period, they're going to have trouble with learning throughout their education, which, indeed, they may shorten to their own detriment.

What's interesting is there seems to be a bit of a generation gap when it comes to hearing aids for children. Recently, my wife prescribed hearing aids for a little boy. His mother wanted skin toned hearing aids, perhaps so no one would notice. He wanted the purple dinosaur hearing aids because they were cool. As, indeed, they are. At least for a little boy. I decided against the purple dinosaur hearing aids!

## 6 The future

My immediate future includes annual hearing tests to make sure my hearing loss hasn't progressed further down the frequency scale. I like to think that my decision to wear hearing aids may inspire others. After at least 25 years of denial, my sister has finally been fitted with hearing aids. And I know more than one acoustician who could benefit from hearing aids. Hearing aids create a better life. Not just for adults but, much more importantly, for children who are just starting school.

I'll finish with a positive story.

A few years ago I was teaching a course on acoustics at the University of Toronto. A young woman came up to me at the beginning of the lectures and asked if I would wear a transmitter for her. This is something that you wear around your neck and it transmits your voice directly into her hearing aids. Her hearing loss was much more profound than mine. My guess is that she's had it all her life. You could tell by the way she talked. I might also guess that, when she was a little girl, her parents were smart enough and open minded enough to get her the proper treatment. I was proud to wear that transmitter for her. Imagine. A young woman who overcame all of the educational challenges imposed on her by a profound hearing loss throughout her entire life and was about to complete a Master's of Architecture degree. Good for you girl! Hearing aids can and do make a difference.

## Acknowledgements

I should like to thank my audiologist Jacqueline Hayden. Her talent and dexterity with the nuances of her profession are very impressive indeed. Plus, she put up with me through all those years when I was in denial! I should also like to thank my friends Peter Alberti and Jerry Hyde. Peter is an otolaryngologist and Jerry is an acoustician. Both wear hearing aids. It was nice to chat with people in the same boat as me.

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# METHODOLOGICAL TRADE-OFFS FOR DUAL-PURPOSE PHONETIC FIELDWORK

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## 1 Introduction

This paper discusses dual-purpose phonetic fieldwork in Hän (Dene/Athabaskan), where ultrasound overlay videos for instructional and cultural purposes could also be important from a linguistic point of view even though they do not follow the standards in the field for ultrasound work. The ideal standard often taught to aim towards has a number of features which can be impossible in many field situations, and by necessity and design were not adhered to very much for the Hän recordings. But we argue that it is important to challenge the rules for what science has to be in order for this kind of work to happen.

## 2 Context

### 2.1 Ultrasound Overlay

Ultrasound overlay videos involve the superposition of ultrasound imaging of the tongue onto facial profile videos in order to serve as instructional materials [1]. Bliss et al. [2] used this technique to develop instructional and cultural materials for Indigenous communities by creating custom overlay videos of community members which highlight difficult sound contrasts in the languages for learners.

Figure 1 shows an example from a previously made overlay video. These videos show the movement of the tongue (the ultrasound video) superimposed over video of the speaker's profile. Previous work on different languages [3] has found that use of these videos improves students' production and perception of certain sound in Cantonese.

### 2.2 Hän

Hän is a Dene/Athabaskan language spoken in Eagle, AK and Dawson City, YK with 6-7 native speakers remaining. Revitalization efforts are currently underway. For example, there is a teacher certificate program offered through the Yukon Native Language Centre and Hän language and culture classes taught in the school system. A priority for the communities is to develop new language curriculum and materials to further the language teaching efforts.

Some acoustic work has been done on Hän [5], but there have been no systematic articulatory studies to date. As Hän is known for its large phonemic inventory, being tied for first as the language with the most affricates and containing a 5-6 way contrast in the coronal region [5], articulatory work on the language is of interest for phonetic and phonological theory.

**Figure 1:** Screenshot from Ultrasound Overlay Video

### 2.3 Challenges

Ultrasound work has quite strict methodological standards such as precise head and probe stabilization, and fully controlled phonological environments and speaker groups. These can prove to be impractical to include in many field situations. These standards by necessity and design could not be fully adhered to for the Hän recordings.

## 3 Procedure

Fieldwork for the creation of the Hän overlay videos took place in a small, quiet room at the Tr'ondëk Hwëch'in Government building in Dawson City during a language curriculum development workshop. Four Elders (3 female, 1 male) who were native speakers of Hän aged 60-90 were recorded. Three spoke the Eagle dialect of Alaska and one spoke the Tr'ondëk Hwëch'in dialect of Dawson City.

An EchoB portable ultrasound was set up on a table in front of the speakers and connected to a laptop where ultrasound and audio could be recorded in Articulate Assistant Advanced (AAA), a software for recording and analyzing ultrasound. Audio was recorded using an AudioTechnica AT831b lapel microphone, pinned to the speakers' shirts. Audio and ultrasound video were synced with an Articulate Instruments Pstretch 1.1 and ClimaxDigital USB 2.0 Audio Capture. Facial profile video was recorded on a Canon ZR950 camcorder and is to be synced with the ultrasound using Adobe Premiere, where the two will be edited into overlay videos.

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During the recording procedure, the Elders were seated at a chair in front of a blue screen and instructed to hold the ultrasound probe very steadily under their chin. The word list was presented on a computer screen in front of them. The camcorder and AAA were set to record and a clapper was clapped, signaling that the speaker could start reading. Two speakers who could not read Hän very well were usually prompted with the words' English meanings, and words were adjusted or switched for other words when speakers were unfamiliar with them. They repeated each word at least twice per recording. The word list was divided into sections by manner of articulation so that there were 6-12 words per section and recorded section by section. Each section was repeated twice for a total of at least 4 repetitions per sound. If the probe shifted during recording, the investigator adjusted the speaker's grip and re-recorded from prior to the shift.

Words were selected such that target consonants were root-initial, followed by a low vowel, [ɑ] or [æ], and wherever possible preceded by the prefix [wə-] 'his/her/its'. Target vowels occurred as the sole vowel of the root, and whenever possible were preceded by post-alveolar onsets.

## 4 Discussion

A number of adaptations from the "ideal" set up were necessary in this particular fieldwork situation.

Head stabilization can be very tricky when dealing with older subjects in the field. Standard ultrasound headsets are not appropriate with elders while probe holding devices and the head resting against a surface, as recommended in [4], are not very effective, obstructing the facial profile video. Further complications arise as the participants often turn or move to look at the investigator any time they forget or can't read a word or don't recognize a word. It was found that this movement could be somewhat mitigated by the investigator standing in front the speaker. The solution chosen here was the have the elder hold the probe – the method was the best choice but it must be noted that it is also not very effective as the speakers are not used to the rigour of keeping still for so long.

Target word choice is, of course, limited by the language. Words with target consonant sounds in low-vowel environments where the nearest consonants are labial consonants are the ideal but not always available in the language. Hän and other Dene/Athabaskan languages have an abundance of low vowels but very few bilabials. There is, however, a prefix with a labiovelar approximate – [wə-] 'his/her' – so the words chosen employed this prefix.

The age of the participants precluded collecting large numbers of repetitions. The ideal number is usually about 6 -10 but this number can easily prove taxing to older participants. This study aimed for a minimum of 4 instances of each word per speaker, which was found to be an appropriate number.

Field work in a language with a tiny number of speakers often may not, by necessity, allow for control of dialect. The language studied here has only 6-7 speakers left and the 4 recorded included 3 speakers of one dialect and one from another. Speakers also knew words that others didn't know, meaning that the wordlist had to be adjusted somewhat depending on the speaker.

**Figure 2:** Hän Overlay Videos Recording Set-up

## 5 Conclusions

Despite the methodological limitations involved in dual-purpose fieldwork, we argue that it is important to consider the possibility of drawing linguistic insights from data collected for instructional purposes. Otherwise, these insights simply wouldn't exist as work with these communities is limited.

## Acknowledgments

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# CROSS-LINGUISTIC BRACING: A LINGUAL ULTRASOUND STUDY OF SIX LANGUAGES

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## 1 Introduction

Lateral bracing refers to persistent and active contact of the sides of the tongue along the upper molars or palate. Evidence from articulatory analysis of native English speakers as well as from 3D biomechanical simulations suggests that bracing of this kind provides mechanical support consistently throughout speech (Gick et al. 2017, Stone 1990). Release of lateral bracing occurs only during some instances of low vowels and lateral consonants. The current study tests for the presence of active lateral bracing in single-speaker case studies of six languages: Cantonese, Korean, Mandarin, Portuguese, Spanish, and Turkish. Based on the point of view that tongue bracing is a fundamental aspect of human speech production, we hypothesize that tongue bracing should exist in speech regardless of language.

## 2 Method

Six speakers of different native languages (Cantonese, Korean, Mandarin, Portuguese, Spanish, Turkish) were asked to read translated passages of the North Wind and the Sun (International Phonetic Association, 1999) in a fluent reading manner, three times each in both English and in their native language while a coronal ultrasound video (Aloka PROSound SSD-5000) of their tongue was recorded in B/M-mode with a six-second sweep speed and with vertical intersect lines placed at three points along the tongue: tongue midline (M), left (L) edge and right (R) edge (see Figure 1). The probe was positioned to capture the video at a coronal cross-section intersecting the tongue roughly as far back as the upper molars. The accompanying audio was also recorded.

The movement of the tongue at the three positions was traced and measurements of the vertical motion were taken from still frames of the M-mode ultrasound videos (each frame displays six seconds of movement trajectory). Active lateral bracing is implicated if the left and right edges of the tongue are (i) less variable in vertical motion than midline and (ii) positioned at a stable baseline height for a larger percentage of time than they are lowered. Two measures are used to assess these criteria: (i) within-speaker comparisons of the amount of variability in vertical movement between central (midline) vs. lateral (left and right edge) positions, and (ii) proportion of time during which one or both sides of the tongue move below a fixed point on the ultrasound. For the variability measure, vertical movement distances were extracted at every pixel along the traced line for each position. For the pervasiveness measure, a baseline height was determined from the line tracings of each speaker and the duration of tongue height below baseline ("releases") is measured. The bottom half of Figure 1 shows vertical displacement trajectories (in yellow) as the tongue moves through the three intersect lines. Percentage of speech that is laterally braced is compared across speakers.

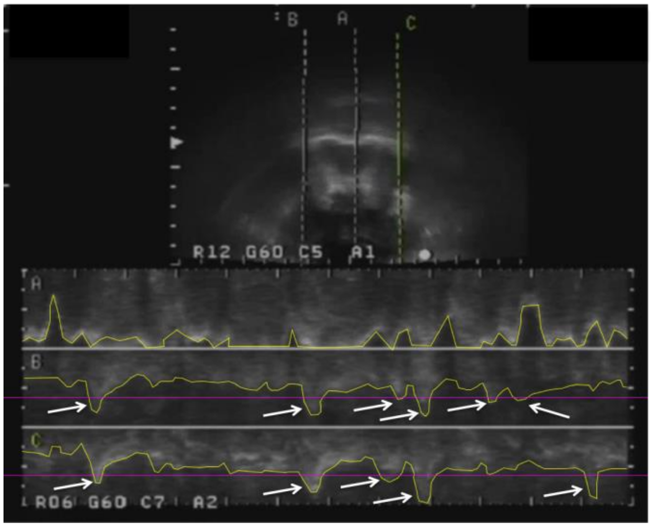

**Figure 1:** Ultrasound image in M-mode for mid (A), left (B), and right (C) positions on tongue. The horizontal lines represent the baseline cut-off and the arrows mark the events identified as discrete instances of lateral release.

## 3 Results

Figure 2 shows the mean vertical displacement of the tongue through the three intersect lines, by speaker. This figure indicates how much the tongue moves vertically along each of the 3 lines (Left, Middle and Right); higher values here indicate greater movement. The graphs indicate greater movement of the tongue midline than of either edge, suggesting more stable placement of the lateral edges of the tongue than the midline throughout speech. It is also interesting to note that all of the speakers seem to move the left side of the tongue more than the right side.

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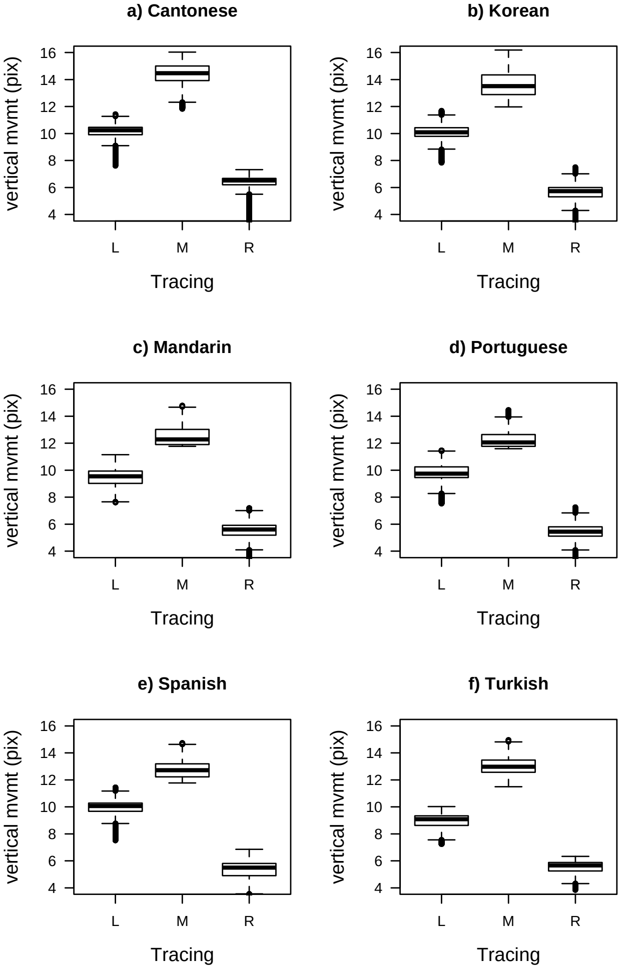

**Figure 2:** Box and whisker plots of vertical movement for each tongue position. Higher values indicate greater movement.

A series of ANOVAS with post hoc Tukey tests was run with vertical movement as the dependent variable and tracing as the independent variable for each language. For all languages both left and right side movement of the tongue was significantly different from movement of the centre ($p<0.001$ in all cases).

For each side of the tongue, the maximum and mode of vertical movement y-values of each tracing were taken. We assume the mode is not laterally released so that anything between the mode and the maximum is natural variation. We assume the same amount of variation below the mode as well. We subtracted the difference (vertical distance) between the maximum and mode y-values from the mode y-value, resulting in separate baseline y-values for left and right sides. The more conservative value was then used as the final baseline y-value for both sides of the tongue for each individual. This can be seen in Figure 1 where the horizontal lines superimposed on the M-mode tracing for B and C represents the baseline. The events marked with the arrows are treated as occasions of lateral release.

Table 1 shows the proportion of the total time of the recorded speech that either one or both sides of the tongue moved below the baseline position. While the amount of time with lateral release varied between speakers, all speakers kept both sides of their tongue raised between 78.02% (Mandarin) and 96.77% (Cantonese) of the time.

**Table 1**: Proportion of speech time with lateral release expressed as a percentage of total time.

| LANGUAGE | PROPORTION RELEASE |
|---|---|
| Cantonese | 3.23% |
| Korean | 8.82% |
| Mandarin | 21.98% |
| Portuguese | 14.43% |
| Spanish | 13.58% |
| Turkish | 18.78% |

## 4 Discussion and conclusions

All six speakers showed significantly more movement of the middle of the tongue than of the sides of the tongue (Figure 2), and all six speakers spent the majority of their speaking time with the sides of their tongues held in a raised position (Table 1). The speaker who held the sides of the tongue lowered for the longest proportion of time (the Mandarin speaker) still maintained a raised tongue position almost 80% of the time. The range of time varies considerably but it must be noted that although all speakers read a version of The North Wind and the Sun, these passages are not balanced for phoneme frequency so the number of phonemes which require loss of lateral bracing differs considerably from one translation to the next.

These results support our hypothesis that lateral tongue bracing is maintained throughout running speech not only in English but in a variety of languages.

## Acknowledgments

The authors wish to thank the six speakers for participating in this study and special thanks to Colin Jones, Victoria Choi and Kate Curtis for their help with analysis.

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# HEARING AND MEMORY DEFICITS IN OLDER ADULTS USING TELEHEALTH

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## 1 Introduction

It is well known that hearing abilities decline with age, and this is due to changes in both the physical structures of the cochlea as well as central processing of incoming acoustic information [1]. Age-related hearing difficulties often manifest in challenging listening situations, such as trying to understand speech in a noisy environment [2]. In these situations, older adults engage top-down cognitive processes to help overcome age-related reductions in the quality of incoming acoustic information [3]. For example, if the final word of a sentence is predictable, age-related differences in understanding that word are reduced compared to when the final word of the sentence is not predictable [4]. Interestingly, the use of these additional cognitive processes to understand speech leads to increased difficulty remembering speech because there is a limited pool of cognitive resources available [5].

One situation where this memory deficit may manifest is when older adults use Telehealth for their healthcare. Telehealth systems connect patients with healthcare providers by using video-conferencing equipment. Telehealth systems rely on audio compression algorithms to facilitate transmission of acoustic information through the internet/telephone lines, resulting in mild to moderately degraded speech signals. Older adults living in rural communities, where specialist physicians are limited, often have to rely on Telehealth to access healthcare. Telehealth has been operating in Newfoundland and Labrador for over 30 years, and includes more than 57 sites across the province [6]. Given previous research, it is possible that older adults may not remember all of the information provided via Telehealth due to the effort required to listen and understand what is said during the session.

Forgetting what was said during Telehealth sessions can have significant health consequences for older adults. Thus, the goal of the present study was to assess the impact of hearing abilities on the ability to retain information provided via Telehealth in older adult users of Telehealth

## 2 Method

### 2.1 Participants and procedure

Thirty-one participants completed the study. Participants ranged in age from 48-82 (*M*=63.9; *SD*=8.2) and 15 were female. All participants were older adult users of Telehealth from the province of Newfoundland and Labrador. Over 500 surveys were mailed to Telehealth sites across the province. After an individual completed a Telehealth session, an assistant would ask the patient if they would like to complete a survey. If they agreed they were given a copy of the survey, an information sheet about the research and a return envelope. An online version of the survey was also available via surveymonkey.com, and additional participants were recruited to complete this survey through advertising on social media and ads posted at Telehealth sites across the province. Ethics approval was obtained from the provincial Health Research Ethics Board (HREB) of Newfoundland and Labrador and the Research Review Committees of Labrador-Grenfell, Western, Central, and Eastern Health.

### 2.2 Materials and data analysis

Participants completed a 29-item self-report questionnaire online or on paper. In addition to basic demographics, participants were asked to rate how often they had trouble remembering something in the past year (*Memory*), how well they could remember health information provided during Telehealth sessions (*TeleMemory*), and how well they could hear the healthcare provider during Telehealth sessions (*TeleHear*), all using 5-point Likert-type scales, where higher numbers indicate better memory or hearing. The survey also included the Hearing Screening Inventory (HIS) [7]. The HSI is a reliable and cross-validated predictor of the 0.5 - 4 kHz pure-tone average. A HSI score above 27 is suggestive of hearing impairment (i.e., > 25 dB hearing loss). Using HSI scores with 27 as a cut-off, participants were divided into two groups: (1) Hearing-Loss group (HL; N=15), and (2) Normal-Hearing group (NH; N=16). Within the HL group, 5 participants wore hearing aids (3 bilateral), while none of the participants in the NH group wore hearing aids. *TeleMemory* was analyzed using an ANOVA that included Group (NH, HL) as a between subject factor, and *Memory* and *TeleHear* as covariates.

**Table 1:** Demographics.

| **Variables** | **Hearing-Loss** | **Normal-Hearing** | ***p-value*** |
|---|---|---|---|
| Age | 66.40 (9.15) | 61.56 (6.61) | ns |
| Gender (% Female) | 53.3% | 43.8% | ns |
| Years of Education | 11.13 (2.17) | 9.56 (2.87) | ns |

## 3 Results

Groups were matched in terms of age, gender and years of education (see Table 1). The HL group, compared to the NH group had lower *Memory* scores (t (29) = 2.61, p = .014) and lower *TeleHear* scores, although this was only significant at a trend level (t (29) = 1.89, p = .07). Participants in the HL group also had lower *TeleMemory* scores, (t (29) = 3.52, p = .001). Most importantly, the difference between the HL and NH group for *TeleMemory*

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remained significant when controlling for both *TeleHear* and *Memory* (F (1, 27) = 5.73, p = .024; see Figure 1).

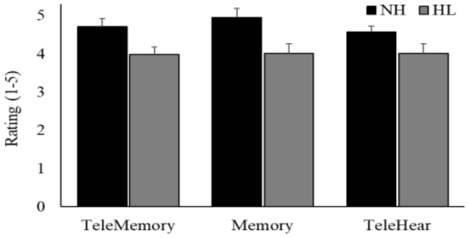

**Figure 1:** Self-report ratings for the *TeleMemory, Memory* and *TeleHear* variables across Group. Higher scores = better ability.

## 4 Discussion

Older adults with hearing loss, as identified by the HSI [7], reported more difficulty remembering information provided via Telehealth compared to older adults with no hearing loss. This effect remained significant after controlling for self-reported memory difficulties over the past year and the ability to hear the healthcare provider during Telehealth sessions. This pattern of results suggests that older adults with hearing loss have a specific memory deficit for information provided via Telehealth.

Individuals with hearing loss have to exert more cognitive effort to understand speech compared to normal hearing listeners [8]. Previous work has shown that this increased cognitive effort reduces the cognitive resources available to remember speech in difficult listening situations [5]. Thus, older adults with hearing loss likely remember less from Telehealth sessions because they have to use extra cognitive resources to process speech from Telehealth.

The sound quality of the speech presented via Telehealth sessions is degraded compared to the sound quality of in-person speech. In Newfoundland and Labrador, the Telehealth system relies on professional grade teleconferencing equipment (e.g., Polycom), that uses a proprietary algorithm to compress and transmit digital audio/video via the internet. Each Telehealth session is compressed at a level that is dependant on the amount of bandwidth available, thus each Telehealth session may have a different level of sound quality. Due to privacy concerns, data regarding the quality of individual Telehealth connections were not available for the present study; however, most participants rated their ability to hear the Telehealth session as good (i.e., ≥ 4/5). There was however, a trend for the HL group to rate their ability to hear the Telehealth session as lower than the NH group. Even when controlling for this trend-level difference in *TeleHear,* the HL group reported a subjective memory deficit for information provided via Telehealth that was greater than the NH group. This suggests that older adults with hearing loss use more cognitive resources to understand Telehealth sessions compared to older adults without hearing difficulties. In turn, this reduces the cognitive resources available to encode Telehealth information into memory.

A second complimentary explanation of the subjective memory deficit in the HL group is that the Telehealth system reduces the supportive and contextual visual cues that can assist in speech understanding. Previous work has shown that speech understanding is better when mouth movements match the speech, and hand gestures are visible, particularly for those with hearing difficulty [9,10]. Although all participants rated the visual quality of Telehealth to be good (i.e., ≥ 4/5), it is possible that there is a reduction in the visual cues available to assist in speech understanding when using Telehealth. For example, a small delay between visual and auditory information could reduce the ability to match mouth movements to speech, and a limited field of view could impair the ability of patients to see hand gestures from healthcare providers. These small differences in visual input would require increased use of cognitive resources to process and understand speech, especially for those with hearing loss, and could contribute to a subjective deficit in the ability to remember health information provided via Telehealth.

## 5 Conclusion

Older adults with hearing loss report increased difficulty remembering information provided via Telehealth. This memory deficit is likely due to having more difficulty understanding speech presented via Telehealth, which results in increased use of cognitive resources that take away resources required to encode information into long-term memory. Forgetting what was said during Telehealth sessions can have a significant impact on the health of older adults who rely on Telehealth. Given the necessity of Telehealth for older adults in rural locations, future work should identify ways to mitigate this memory deficit.

## Acknowledgments

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# TOWARD A METHOD TO UNCOVER L1 JAPANESE SOCIOPHONETIC TRANSFER TO L2 ENGLISH

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## 1 Introduction

Understanding the acoustic socio-phonetic reality of intelligibility in spoken English is of theoretical importance to linguistic and applied linguistic research and in demand as English is a common lingua franca across the globe. To understand the factors that improve intelligibility of L2 English necessitates an interdisciplinary approach that combines phonetics, second language acquisition to uncover socio-cultural meaning on what constitutes intelligibility for L2 English speech from the perception of the native English speaker (NES) as the listener. We propose mixed methods research to study the prosodic feature of voice pitch and its role in intelligibility in L2 English speech. In this paper, we discuss how voice pitch is perceived in terms of intelligibility in L1 to L2 English phonetic transfer.

In L2 speech evaluation research, intelligibility is generally understood as “actual understanding of a word or utterance” [1]. Intelligibility then is the speaker’s ability to convince the listener of the speaker’s meaning of the words, intention of the sentences conveyed, and emotion behind the utterance, which should be expressed in appropriate content and form. At the form level intelligibility can be associated with various phonetic and non-verbal features such as prosody, rhythm, tone and pitch of speech. However, a language-specific prosody could negatively transfer to L2 speech and affect L2 intelligibility [1]. There is no research testing how these aspects can affect the intelligibility of L2 English.

Previous studies have investigated intelligibility in relation to pronunciation errors [2] at the segmental level, foreign accent [3], paralinguistic features contributing to the intelligibility of non-native English speakers [4], voice pitch, quality, politeness and gender specific to Japanese [5] and prosodic cues that transfer between L1 and L2 [6]. Despite the number of crosslinguistic transfer studies in intelligibility, studies in how voice pitch is perceived in terms of intelligibility and socio-cultural meaning has not been done. The research questions are two folds:

- How is the pitch range and intensity of spoken English of EFL learners related to the levels of L2 proficiency?
- How does the pitch/intensity manifestation affect the intelligibility of L2 English from the view of the native English speaker (NES)?

## 2 Method

Sixteen EFL learners at the average age of 19 in a Japanese university were asked to deliver a one minute speech about themselves, both in English and Japanese. Avideocamera was mounted in a CALL classroom, and a microphone was pinned on the neck of the speaker’s shirt. They were told to talk to the camera.

As a first approximation, we made a prediction about the relation between the efficiency of English and the use of pitch and the intensity; Advanced EFL learners, compared to beginners, should show (i) more dynamic pitch range, and (ii) larger intensity, which should contribute to the intelligibility. Another prediction is that advanced learners may switch the tone of voice between two different linguistic settings.

We chose 6 female students only. One speaker was an ‘advanced’ (C1 level in CEFR, 751-900) learner of English, four were at ‘upper intermediate’ (B2 level in CEFR, 526-750), and one was at ‘pre-intermediate level’ (A2 level in CEFR, 300-400) according to the categorization of embassyenglish.com. Self-reported TOEIC scores were used as a measure of objective English skills of individuals. Students were later asked to pick one most important (meaningful) sentence in their own English speech. Pitch and intensity of the targeted English sentence and the Japanese equivalent were measured in Praat [7] for each person. In pitch setting, semitones were set re 1Hz, for interspeaker comparison. For the quantification of the pitch range, we used the output of the maximum pitch minus minimum pitch.

Four NESs of American English in the western part of the United States volunteered to view videotapes to comment on voice pitch and L2 English intelligibility. They were all naive about Japanese language. Each NES volunteer is identified by gender (F=female/M=male), age and nationality (A=American) as F19A, M28A, F57A and M62A. The first volunteer was a college student, and the rest of them were college graduates currently in professional occupations.

## 3 Results

Results indicate that our predictions were right in general. The trendline of both graphs (Fig. 1) show that TOEIC scores on one hand and the size of the pitch range or intensity on the other hand are positively correlated. First, for the pitch of English sentences in question, the average pitch of the individuals of this group was 85.1 Hz, the min

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was 77.3 Hz, and the max was 91.1 Hz. Thus, the difference between them (=pitch range) was 13.8 Hz. Among them, the biggest pitch range was marked 18 Hz by an upper intermediate speaker, and the lowest pitch range was marked 6.2 Hz by a pre-intermediate speaker who was on the lower end of x-axis. Second, the intensity of English speech of the sentences in question was averaged among the six females at 50.6 dB. Among them, the largest intensity was marked 54.6 dB by an advanced speaker who was on the higher end of the x-axis. The smallest intensity was marked 44.3 dB by an upper intermediate speaker.

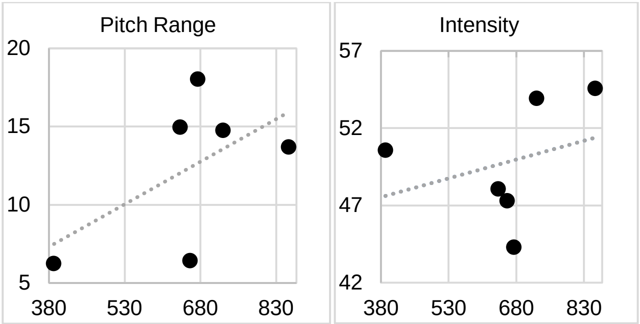

**Figure 1:** TOEIC score (points; x-axis) and pitch range (Hz; y-axis) on the left, and intensity average (dB; y-axis)

Another finding was the difference in pitch height between the two speech settings. The y-axis below shows the pitch value (Hz) calculated by pitch used in Japanese speech minus pitch used in English speech. The average of this value of all individuals is 0.3 Hz, which suggests Japanese speech is 0.3 Hz higher than English speech in general.

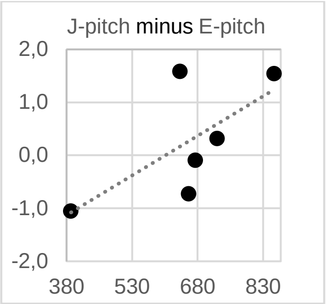

**Figure 2:** TOEIC score (points; x-axis) and the difference in pitch (Hz; y-axis) between English speech and Japanese speech

It is worth noting that an advanced learner (higher end of x-axis) lowers pitch in English relative to Japanese, while a pre-intermediate learner (lower end of x-axis) raised pitch in English relative to Japanese. The upper intermediate group was split into two groups; Two speakers lowered pitch in English and the other two raised pitch in English.

## 4 Discussion

Previous research shows that women tend to use high soft pitched voice as a societal expectation to project a feminine image [5] (p.14) and as a manifestation of politeness [5] (p.127). Americans however view softness of pitch differently. Soft pitched voice particularly in American women is generally seen as an undesirable trait of timidity and therefore lacking in authority (Key and Kramer study as cited in [5]).

These findings are compatible with how American viewers' commented on Japanese EFL speech. M28A interpreted the high soft pitched voice of a Japanese woman's English speech: *"Very timid English speaking"* In another comment M28A wrote that he wished for a louder voice, saying *"[she] was very quiet and it would be easier [to hear] if she speaks up."*

A key factor in intelligibility is not only to hear the speaker but to be able to hear the speaker clearly. F19A stated that intelligibility was lost because of indistinct sounds, saying *"The English speech sounded mumbled by the students on the right because of how softly they spoke."* F19A speaks to the notion that soft speech is not valued or stigmatized in American culture, as listeners must strain to make out distinct pronunciation sounds and thus soft tone is seen as undesirable. F19A added that soft speech was also monotoned. F19A's commented it is not so much that the speech was unintelligible, but there appeared to be a lack of interest in the speech.

## 5 Conclusion

Results show i) we are on a right track in examining whether levels of L2 English are correlated with the expansion of pitch range, augmentation of intensity, and lowering of pitch in L2 English in relative to L1 Japanese, and ii) there is a difference in socio-cultural meaning as far as voice pitch and intensity are concerned from the view of the American listeners. Further research will investigate additional paralinguistic factors that influence intelligibility of L2 English with augmented data.

## Acknowledgments

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# THE IMPACT OF DIALECT ON THE ABILITY TO UNDERSTAND SPEECH-IN-NOISE

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## 1 Introduction

Difficulty understanding speech-in-noise (SIN) is one of the most commonly reported hearing issues for older adults. Thus, being able to accurately assess an individuals' ability to understand SIN is of utmost importance. A number of standardized assessments have been developed to quantify this ability, such as the QuickSIN [1]. In general, these tests use pre-recorded speech as the target stimulus, and thus the language and dialect of each test cannot be easily modified. One issue that has received scant attention is how dialect impacts performance on a standardized SIN test.

Previous work has demonstrated that dialect can impact the ability to understand speech-in-noise. When target speech was a non-native dialect (e.g. Japanese speaker, speaking in English), the ability to understand the speech was impacted by how dissimilar the dialect was from the native dialect of the listener [2]. Bilingual participants were worse at understanding SIN in their second language compared to their native language, and the difference in performance was reduced as second language proficiency increased [3]. In the USA, regional dialects were harder to understand in background noise, compared to a 'general American' dialect, suggesting that understanding mismatched speaker-listener native English dialects is more difficult compared to when there is no mismatch [4]. Interestingly, the effect of speaker dialect did not interact with listener dialect, suggesting that in geographically connected regions, the dominant dialect is equally understandable in noise, even for speakers of a different dialect [4]. It is therefore possible that speakers of dialects from a geographically isolated region might perform worse on SIN tasks in the more common dialect.

This putative impact is critically important for speakers of dialects that do not have standardized SIN assessments in their native dialect. The potential negative impact of speaker-listener dialect mismatch could lead to inaccurate audiological assessment, and increased variability in research. One region that has a distinct English dialect and is geographically isolated is the island of Newfoundland; within Newfoundland, areas outside St. John's (i.e., main population centre) are further isolated from speakers of non-Newfoundland dialects of English. Accordingly, the goal of this study was to examine if people with normal hearing from Newfoundland perform outside of the norms for the QuickSIN test.

## 2 Method

### 2.1 Participants

A total of 56 participants between 18 and 39 years old (41 women, and 15 men; $M_{\text{age}} = 22.16$, $SD = 5.33$) were recruited from Memorial University, Grenfell Campus and from the community. Grenfell Campus is located in Western Newfoundland. All participants were native English speakers born in Newfoundland to parents who were also born and raised in Newfoundland. All participants described their English dialect as being Newfoundland English.

### 2.2 Procedure, stimuli and task

All stimuli were presented through Sennheiser HD200 headphones, while participants were seated in a double walled sound-attenuating booth. A demographics questionnaire was administered orally by the researcher. Pure-tone thresholds were collected for each octave from 250-8000 Hz. The impact of dialect on speech-in-noise was assessed using lists 1-5 from the QuickSIN (Etymotic research) at 75 dB SPL. All participants also did a practice list before the experimental lists were presented. The results from QuickSIN are presented in decibels signal-to-noise ratio loss (dB SNR), with 0 dB SNR representing the expected performance of a listener with normal hearing [1]. Killion et al. [1] also calculated confidence intervals (CI) around 0 dB SNR. The CIs around 0 dB SNR are smaller as more lists are used. These CIs were used to compare the current sample of speakers of Newfoundland English.

## 3 Results

All participants had normal audiometric thresholds (i.e., below 25 dB HL from 250-8000 Hz). The dB SNR loss from lists 1-5, and the mean dB SNR loss from those 5 lists are presented in Figure 1. As a first step, performance on each individual list was compared to the expected performance of 0 dB SNR loss. Performance on each list was significantly above 0 dB SNR ($t(55) = 3.5$-$12.9$, $p \leq .001$ for all), Next, performance was compared to the single list 95% CI (2.7 dB SNR loss) from Killion et al., [1]. Performance on lists 1, 2 and 4 was significantly below the 95% CI boundary (i.e., performance was within the normal range; $t(55) = -1.89$, $p = .06$; $-7.69$, $p < .001$ & $-4.74$, $p < .001$). Performance on lists 3 & 5 was not significantly different than the boundary of the 95% CI ($p > .45$ for both). Averaging performance across the five lists increases reliability, thus decreasing the CI [1]. When comparing average performance across the five lists to the CI for five

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lists, dB SNR loss was above (i.e. worse) the 95% CI boundary (1.2 dB SNR loss; $t(55) = 5.02$, $p \leq .001$).

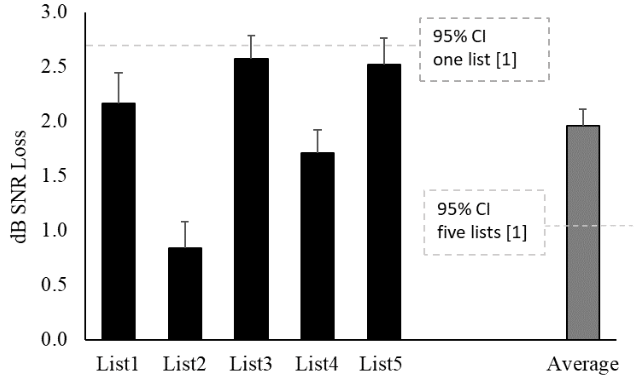

**Figure 1:** Performance on lists 1-5 of the QuickSIN test, and their average. 95% confidence intervals from [1] are shown to highlight how participants from Newfoundland compared to the norms.

## 4 Discussion

The present study found that Newfoundlanders performance on the QuickSIN was outside the norms when considering five lists. Performance on each individual list was higher than normal, but did not fall outside the 95% CI [1]. All participants had normal hearing as assessed by pure-tone audiometry. This finding provides support for the hypothesis that it is more difficult to understand SIN in a non-native dialect. Most critical, the findings suggest that speaker-talker dialect mismatch can negatively impact audiological assessment and may impact research that uses standardized SIN assessments.

Previous research has found that that speaker-listener dialect mismatch results in increased difficulty understanding SIN [2]–[4]). However, this effect seems to be mitigated when the speaker is using a ‘dominant’ regional dialect [4]. Although the QuickSIN test was recorded in the dominant North American English dialect, people from Newfoundland performed outside the norms. This suggests that geography may play a role. The isolation of Western Newfoundland from the rest of the continent means that people in this region are less exposed to that dominant dialect. The current findings, taken in concert with previous work showing little impact of dialect-speaker mismatch on SIN perception when using continental American dialects [4], suggest it is likely that ‘in-person’ experience and exposure to a native English dialect can mitigate the impact of dialect difference on the ability to understand SIN. One possible mechanism for Newfoundlander’s difficulty understanding SIN in a non-Newfoundland dialect is based on the *framework for understanding effortful listening* described by Pichora-Fuller et al. [5]. In general, this model highlights that there is a limited amount of cognitive resources available to process and understand speech. When listening to a less familiar dialect, differences in speech prosody, vocabulary, vowel sounds, and other dialectical differences increase the cognitive resources required to understand the speech. In quiet situations, cognitive resources are available to process dialectical differences, so the speech can be understood. When there is background noise, additional cognitive resources are needed to perceptually segregate the speech from noise. Accordingly, when the noise level reaches a certain threshold, there are not enough cognitive resources available to simultaneously segregate the speech from noise and process the dialectical differences. In this situation, the speech can no longer be understood. Limited cognitive resources are the likely source of the impact of dialect on SIN understanding as the participants in this study were young healthy adults, with normal audiometric thresholds. It is therefore unlikely that the increased difficulty understanding SIN in a different dialect in the current study was due to abnormal peripheral encoding or central auditory processing deficits.

## 5 Conclusion

Native Newfoundland English speakers performed significantly worse on a QuickSIN test compared to the standardized norms [1]. This could lead to potential for misdiagnosis of hearing problems because the QuickSIN test is used clinically. It is therefore necessary to develop a "newfound" norm for Newfoundlanders on the QuickSIN, or to develop a new standardized assessment that uses speech stimuli recorded by a native Newfoundlander. The results of this study highlight the need to accomplish both of these goals.

## Acknowledgments

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# WIND TURBINES - ÉOLIENNES

# COMPARISON OF INTERNATIONAL ENVIRONMENTAL NOISE GUIDELINES FOR WIND FARMS

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## 1 Introduction

Many jurisdictions treat wind farms as they do any other industrial noise source, while some jurisdictions have noise regulations/guidelines/criteria specific to wind farms.

## 2 Canada

The sound propagation model, ISO 9613-2, is widely used across Canada. However, guidelines and criteria vary from province to province. The Canadian Wind Energy Association recommends setback distances for wind turbines based on issues regarding turbine and blade failure, ice shedding, noise, environmental impacts and interruption of communication systems [1].

### 2.1 Ontario

In Ontario, the sound level limits for wind turbine noise are in the Ministry of Environment and Climate Change Publication "NPC-232" [2] as well as "Noise Guidelines for Wind Farms" [3] which explains how the limits identified in NPC-232 are applied to wind farms

In rural areas, sound level limits in terms of $L_{eq,1hr}$ at noise sensitive receptors range from 40 to 51 dBA as wind speeds increase from 4 to 11 m/s. In other zones (suburban and urban) the range is to 45 to 51 dBA.

### 2.2 New Brunswick, Manitoba, Nova Scotia

In New Brunswick, Manitoba and Nova Scotia, the sound level limits are the same as in Ontario.

### 2.3 British Columbia

The "Best Practice for Wind Power Project Acoustic Assessment document", dated 2012, [4] makes recommendations for interpretation of the Land-Use Operational Policy criteria; requirements of assessment reports; and predictive modelling techniques.

The Land-Use Operational Policy requires that sound from wind turbines should not to exceed 40 dBA in terms of $L_{eq,Night\ (2200\text{-}0700)}$ and $L_{eq,Day\ (0700\text{-}2200)}$ on the outside of a permanently-occupied residence or the nearest property line of undeveloped land parcels zoned for residential uses at the time of application to construct a wind farm, where ambient is 35 dBA or less.

Where ambient is greater than 35 dBA, day or night (except where another wind power project is present), a 5 dBA increment may be applied to a measured background sound level, to a maximum criterion of 50 dBA.

The BC guidelines recommend ISO 9613-2 as the sound propagation model. However, CONCAWE, Harmonoise and Nord2000 models may be used with explanations of particular effects being modelled.

### 2.4 Alberta

Rule 12, of the Alberta Utilities Commission, concerns noise control for all energy facilities including wind farms [5].

The CONCAWE model is recommended alongside ISO 9613-2 with additional adjustments specifically for wind facilities. The turbine sound power level must be the maximum emitted when the turbine operates under planned maximum operating conditions for both day and night. The model must include the cumulative effects of adjacent wind farms and other energy-related facilities that may impact a dwelling. Where no dwelling exists within a 1.5 km radius of the wind farm, and the proposed facility is adjacent to an existing facility, which also has no dwellings with a 1.5 km radius, then the sound level may exceed the permissible limit where the two radii overlap.

Criteria at receptors are determined on a case by case basis based on proximity to heavily travelled transportation noise sources and density of settlement. The criteria range from $L_{eq}$ (8hr) 40 dBA to 56 dBA.

## 3 Europe

Many countries in Europe use the World Health Organization Guidelines for Night Noise as the base criterion, where $L_{eq}$ over 8 hours (23:00 – 07:00) outdoors should not exceed 40 dBA [6].

### 3.1 Denmark

Denmark previously used their own sound propagation model with criteria ranging from 37 dBA at wind speeds of 6 m/s in noise sensitive areas up to 44 dBA at wind speeds of 8 m/s in open country. Now the Nord2000 propagation model is recommended. A correction of +1.5 dB for ground effect is used for land based wind farms. For offshore wind farms, the correction is +3 dB.

### 3.2 Sweden

The Swedish Environmental Protection Agency has guideline limit of $L_{eq,24hr}$ of 35 dBA for Natura 2000 (environmental protection) areas. The commonly used

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model is ISO 9613-2 with additional considerations for cylindrical spreading over water for offshore wind farms.

### 3.3 United Kingdom

In the UK, both the Marine Management Office and Department of Energy and Climate Change are responsible for assessing offshore wind farms. Both agencies require projects to be assessed using the ISO 9613-2 and/or CONCAWE models.

For noise assessment, the ETSU-R-97 guidance developed by the Noise Working Group for the UK Department of Trade and Industry, was used to scope the impact of the wind turbines on onshore and near-shore sensitive receptors [7]. The day-time limits range from 35 to 40 dB in terms of $L_{90,\ 10\ minutes}$ when the prevailing background noise level is below 30 dBA $L_{90}$. The range allows for considerations of number of dwellings, the amount of energy generated and the duration and level of sound exposure). The nighttime limit is 43 dB.

## 4 Oceania

South Australia, Queensland, Western Australia and New South Wales use “South Australia Wind Farms Environmental Noise Guidelines” [8]. Both Victoria and Tasmania use the New Zealand Standard NZS 6808:2010, “Acoustics – Wind Farm Noise” [9] with the former including a minimum setback distance of 1 km.

### 4.1 New Zealand

NZS 6808:2010 provides guidelines for most of the processes involving noise from wind farms. The noise limit ($L_{90,\ 10\ minutes}$) at most receptors is 40 dBA or the background level plus 5 dBA if the background level is over 35 dBA. In special circumstances, a more stringent limit of 35 dBA or the background level plus 5 dBA, if the background level is over 30 dBA, is applied.

Sound modelling is acknowledged as not being standardized but the ISO 9613-2 model is mentioned as correlating well with measured data for wind farms. It indicates that whichever model is used, the predictions should take into account sound power levels; positions of wind turbines; directivity of propagation; meteorological conditions; attenuation due to geometric spreading, atmospheric absorption, ground effects and obstacles; and barrier/terrain screening. Penalties of up to 6 dBA are applied for a range of characteristics such as tonality, impulsiveness and amplitude modulation.

### 4.2 South Australia

The South Australia guidelines state that a suitable model must be selected (or developed) to predict the worst-case sound level at all relevant receivers. While recognizing that there is no standard procedure directly applicable to sound propagation from wind farms, the guidelines recommend that noise prediction methods in ISO 9613−2 or CONCAWE be used, with atmospheric conditions at 10ºC and 80% humidity, weather category 6 (if CONCAWE), and hard ground (zero ground absorption factor).

The sound level ($L_{eq,\ 10\ minutes}$) in outdoor living areas, due to the new wind farm developments, shall not exceed 35 dBA in rural areas; 40 dBA in other areas; or the background ambient sound level plus 5 dBA, whichever is greater. There is a +5 dBA penalty for tonal components.

## 5 U.S.A. (Oregon)

Most states do not have noise criteria specific to wind farms. In Oregon, Industrial and Commercial Noise Source Standards for a wind energy facility allow the wind energy facility to increase the ambient statistical noise levels $L_{10}$ and $L_{50}$ over 1 hour by 10 dBA using either an assumed $L_{50}$ of 26 dBA or the actual ambient background level measured at an appropriate measurement point (i.e., the further of a point 25 feet in front of the receptor or the point on the property line nearest the noise source.). The sound level limits are 50 dBA ($L_{50}$ over 1 hour) or 55 dBA ($L_{10}$ over 1 hour) at night (2200 to 0700). During daytime, the sound level limits are 5 dB higher.

## 6 Conclusions

The strictest noise requirements are found in Sweden, Germany, Finland, New Zealand, the United Kingdom and parts of Australia. Several countries have penalties for tonal, impulsive, low frequency noise or amplitude modulation of wind turbine sound. Some jurisdictions indicate a particular acoustical modelling method should be used for wind farm noise assessment. Many do not specify nor require a particular modelling method.

The sound limits variously range from 35 to 60 dBA, subject to time of day and other factors such as ambient sound level, typically with the starting point being 35-40 dBA.

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# WIND TURBINE AEROACOUSTIC NOISE PREDICTION USING COMPUTATIONAL MODELS AND COMPARISON TO EXPERIMENTAL MEASUREMENTS

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## 1 Introduction

Energy from wind turbines has enjoyed a remarkable growth worldwide in the past decades. In Canada, generation capacity has increased dramatically. The issue of noise and wind turbines has become a subject of interest for researchers and acoustics practitioners. For utility scale wind turbines, broadband noise emanating from the trailing edge of the wind turbine blade is a large contributor to the overall noise emission. In order to minimize the noise impact, regulatory bodies often set limits to the noise level observed nearby. Good noise predictive tools are necessary to estimate noise emissions for many reasons including wind farm development.

These tools are developed from computational fluid dynamics (CFD) studies using Large Eddy Simulation (LES) in conjunction with the Ffowcs-Williams and Hawkings (FW–H) acoustic analogy to predict the far field sound. These results are compared to results from the use of existing semi-empirical prediction models. Validation of these predictive tools are compared with experimental measurements of 2D airfoil self noise obtained at the University of Waterloo.

## 2 Method

### 2.1 LES simulation

Computing the aeroacoustic noise emitted from a turbine blade requires an understanding of the flow behaviour around the blade. The key parameters needed for acoustic prediction are the pressure and fluid velocity at the surface of the airfoil. For this model, the LES solver in ANSYS Fluent is used with the Dynamic Smagorinsky-Lilly subgrid-scale model [1].

### 2.2 Simulation geometry and setup

Two different external flow cases were tested to determine the feasibility of the acoustic prediction model: a 2D NACA 0012 airfoil, and a 2D SD-7037 airfoil in an enclosure. The first case is a replication of simulations recently reported by Wasala [2] that compare predicted results to those measured by Brooks *et al.*[3]. The second case predicts both static and dynamic airfoil aeroacoustic noise and compares it to experimental results obtained at the University of Waterloo [4]. Table 1 summarizes the system geometry and key simulation parameters. The receiver location for the NACA 0012 experiments was set a distance off of the trailing edge of the airfoil in a direction perpendicular to the chord line. For the SD-7037 experiments, the receiver was located in the lower wall of the wind tunnel, directly below the ¼ chord.

**Table 1:** Simulation setup

| Parameter | NACA 0012 [2] | SD-7037 [4] |
|---|---|---|
| Chord (m) | 0.3048 | 0.0025 |
| Span (m) | 0.1143 | 0.150 |
| Domain Width (m) | 0.1143 | 0.1524 |
| Domain Height (m) | 3.658 | 0.1524 |
| Domain Length (m) | 5.487 | 0.460 |
| Velocity (m/s) | 71.3 | 31 |
| Receiver (m above airfoil) | 1.219 | -0.0762 |

The experiments performed on the SD-7037 airfoil include constant angle of attack (AOA) measurements as well as an oscillating AOA case.

### 2.3 FW-H acoustic analogy

The FW-H analogy is a rearrangement of mass and momentum conservation into an inhomogeneous wave equation that accounts for the presence of an impermeable surface in the flow. The resulting equation has three inhomogeneous terms: a quadrupole term which accounts for sound generated by fluctuating Reynolds stresses, a monopole (or thickness noise) term and a dipole (or loading noise) term. Together, the thickness and loading noise terms represent the sound generated by the body passing through the flow [5]. In the equation below, the quadrupole term contains Lighthill's Tensor ($T_{ij}$), the loading noise term contains the compressive stress tensor ( $p_{ij}$ ) and the thickness noise term contains the fluid velocity ($u_i$).

$$\left(\frac{\partial^2}{\partial t^2} - c_o^2\frac{\partial^2}{\partial x_i^2}\right)\left(\rho' H(f)\right) = \frac{\partial^2}{\partial x_i \partial x_j}\left(T_{ij}H(f)\right) - \frac{\partial}{\partial x_i}\left(p_{ij}\delta(f)\frac{\partial f}{\partial x_j}\right) + \frac{\partial}{\partial t}\left(\rho_0 u_i \delta(f)\frac{\partial f}{\partial x_i}\right)$$

The function, $f(\vec{x},t) = 0$, defines the surface of the body and therefore the quadrupole term applies outside of the defined surface, and the thickness and loading noise terms only apply on the surface of the body. In the case of aeroacoustic noise, the quadrupole term is often neglected since the noise generation is dominated by the thickness and loading noise terms [6].

The solution used for this model is Formulation 1A by Farassat [6], which places an impermeable surface on the blade and calculates the sound propagation using a retarded time frame.

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**ANSYS fluent FW-H built-in solver**

ANSYS Fluent has a built-in FW-H solver that has a similar solution to Formulation 1A [5]. The main difference is the solution uses a semi-permeable surface that can be offset from the airfoil to compute the quadrupole noise for the flow contained within the surface [1]. However, when placed coincident to the airfoil surface, the calculation simplifies to the Formulation 1A solution. The latter method was used for the prediction model.

**Validation of acoustic results**

The accuracy of the simulated results is determined by comparison with appropriate experimental results as well as with semi-empirical prediction from the National Renewable Energy Laboratory (NREL) program NAFNoise [7].

# 3 Results

## 3.1 LES simulation results

Initial simulations of the NACA 0012 experiments indicate good correlation of the flow parameters, including lift coefficient ($C_L$) and coefficient of pressure ($C_p$). The simulated $C_L$ is 0.53 compared to 0.6 in previous simulations [2], and 0.58 in experimental results [8]. The lift coefficient is expected to increase to the appropriate value in simulations with finer mesh resolution at the leading edge of the airfoil.

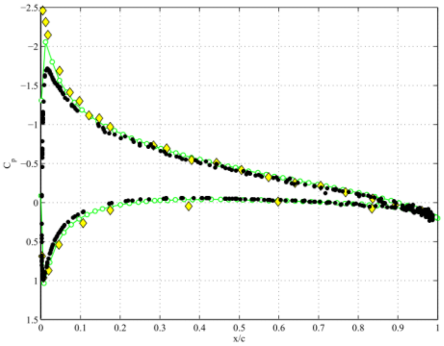

**Figure 1:** Pressure coefficient plot for an angle of attack of 5.4 degrees. Wasala[2] (□) and Gregory and O'Reilly[9] experiments (◊) and present simulated results (•)

Figure 1 shows the simulated $C_p$ with previous simulations [2] and experimental results [9].

LES simulations are sensitive to the mesh quality and requires a very fine mesh to accurately resolve the flow. This is especially true for the trailing edge portion of the blade. Current computational limitations limit the required mesh sizing and result in slight discrepancies in the results.

## 3.2 FW-H acoustic results

To date, preliminary simulations for aeroacoustic prediction resulted in sound power levels (SPL) within the expected range. The 1/3 octave spectra results also follow the appropriate trend when compared to experimental results (Figure 2).

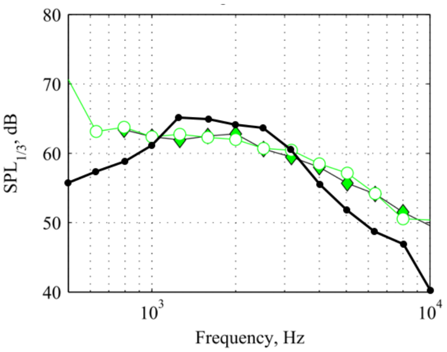

**Figure 2:** SPL plot for an AOA of 5.4 degrees. Wasala[2] (□) and Brooks *et al.* [3] experiments (◊) and present simulated results (•)

In the time between the submission of this paper and the conference date, there is expected to be significant progress on the static acoustic prediction by improving the mesh parameters for the systems. Preliminary simulations on the dynamic SD-7037 system are also expected to be completed.

# 4 Conclusion

The developed predictive tools show good agreement with the measured experimental data leading to further development of the predictive tools. The close agreement of CFD flow properties indicates the feasibility of using the ANSYS Fluent LES and FW-H solvers to predict the areoacoustic noise from wind turbine blades. Accurately simulating of both static and dynamic 2D airfoil systems are crucial building blocks to developing more complex models for full turbine acoustic prediction tools.

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# ABSTRACTS FOR PRESENTATIONS WITHOUT PROCEEDINGS PAPER
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## Insertion Loss And Wind Induced Noise Results For Secondary Wind Screens

*Ian Bonsma, Nathan Gara, Nick McCabe*

Sound pressure level measurements of wind turbines presents a particular problem for microphone self-noise. Wind turbines typical only generate significant sound under higher wind conditions which are not ideal for sound level measurements. As a result, various schemes are used to reduce wind induced self-noise, these include the use of ground boards, larger than typical foam windscreens, and the use of secondary windscreens. HGC Engineering undertook testing to investigate the insertion loss of various oversize windscreen designs, as well as the reduction of wind induced noise offered by these designs. This paper describes the windscreens tested and presents the insertion loss and wind induced noise results.

## Differences In Predicted Far-Field Sound From Wind Turbine Noise Sources Having Comparable Overall A-Weighted Sound Power Levels Using Iso 9613-2

*Kohl Clark*

This paper is based on research conducted by the author through Aercoustics Engineering Limited (Mississauga, Ontario, Canada). The A-weighting curve is a widely adopted method by which sound levels are adjusted to account for the human perception to the sound. This weighting curve applies increasing levels of attenuation for sound at frequencies below 1 kHz. The sound power emission of a given piece of mechanical equipment is often given in terms of an overall A-weighted power level, a logarithmic sum of each 1/3 octave component of the frequency spectra. Due to the nature of this summation, two pieces of equipment may yield similar overall sound levels while having vastly different low-frequency spectral content. This study compares the difference in predicted far-field noise levels from wind turbines that have different 1/3 octave spectra but comperable overall A-weighted sound levels. The focus of this study was on the propogation of wind turbine noise, modelled per ISO 9613-2, using published sound power data from various turbine manufacturers. The impact from wind turbines of similar overall A-weighted sound power ratings was assessed at points of reception placed at varying distances from the turbines.

## Wind Turbine Infrasound Penetration Into Homes Using Narrowband Measurement Techniques

*Andy Metelka*

Measurements using advanced instrumentation and Narrowband 3-dimensional FFT-based signal processing indicate the presence of harmonics at infrasonic blade pass frequencies in dwellings near multiple turbines. Proposed calculations for transmissibility are outlined with simultaneous long-term measurements at four homes. Measurement validation techniques are outlined separating naturally occurring infrasound from wind turbine infrasound. Various locations inside homes are also compared to outside measurements relating wind speed, wind direction and other audible SLM parameters. Simultaneous synchronous measurements indicate levels differ in each room of a home. Higher harmonics inside homes are reduced, however, and become more distinct relative to background infrasound. Older homes with large vented attics tend to couple these pressures into rooms below.

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