OCTOBER, 1980
Vol. 8, No. 4

acoustics and noise control in canada

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l'acoustique et la lutte antibruit au canada

Our cover shows members noisily en route to the Annual Meeting

Simon Tuckett

acoustics and noise control in canada

The Canadian Acoustical Association
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l'acoustique et la lutte antibruit au canada

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EDITORIAL

The editorship of "Acoustics and Noise Control in Canada" changes at the upcoming Annual Meeting. I would like to take a minute to report to the membership how the journal is evolving. For indeed, journals do "evolve", and the publication that the next editor takes over has been nourished by the care of all the previous editors and officers of the association, as much as by the team now in charge. We advance only when previous advancements are taken for granted.

In the last two years, we have successfully shed our government support, and become truly independent of any grant or subsidy. Until 1978, the government maintained our mailing list, printed the journal, and paid for all that and the distribution besides. Since then, Doug Whicker has maintained our mailing list, Deirdre Benwell has arranged our printing and distribution, and Moustafa Osman has sold the mailing list, attracted advertising and sustaining subscribers, and paid not just the bills but made a profit besides. Les Russell has managed the increasingly complex finances.

These administrative tasks have consumed more effort than evidenced by a casual reading of our pages. We hope, however, that other aspects of the editorial effort are visible. Our covers are in colour, and illustrated by Simon Tuckett who also helped us with our logo. Our text now conveys more news, and an occasional photograph, and is often typeset (thanks to the help of Rosemary Garsh). Our papers, which continue to occupy over half of the journal, increasingly come under referees' scrutiny before their acceptance. The referees are to be thanked for their dedication to this most invisible and thankless of tasks.

Our objectives have therefore been fourfold: financial independence; a livelier appearance (though not "gloss at any price"); more news about Canadian acoustics; and a higher standard of published papers.

It is in this last area that the journal is at a stage that will need monitoring and managing in the years ahead.

We have so far chosen not to assume the role of a high-quality scientific journal - which would require an international circulation, an improved format and probably a change of name. It is arguable whether another such journal is needed. Moreover, if we took such a route, and did not make the transition successfully, writing for the journal could be beneath the interest of the best acousticians while beyond the reach of many of our present contributors. Our readability could fall off dramatically.

Our current policy has therefore been to make only evolutionary changes in our acceptance procedures for papers. Our referees stress accuracy and readability before advanced thinking. This policy makes us accommodating to our authors, while still being responsible to our readers. It would succeed better, however, if more authors responded, and we received a greater quantity and diversity of concise, newsworthy material.

As usual, we remind authors that the journal is ready when you are.

JOURNAL PROFIT AND LOSS

At this transition point to a new editorial team, Les Russell, CAA Treasurer, has prepared a profit and loss statement for the journal's last two years.

Vol, No.	Receipts	Expenditures	Profit
7, 1	895.00	476.46	418.54
7, 2	915.00	569.30	345.70
7, 3	1,084.50	783.23	301.27
7, 4	652.50	605.71	46.79
8, 1	1,305.00	644.69	660.31
8, 2	798.30*	656.37	141.93*
8, 3	970.00*	445.54	524.46*
8, 4	565.00*	475.00†	90.00*†
Total	7,185.30	4,656.30	2,529.00

Asterisked figures convey the financial picture expected when receipts are in from recent issues.

Daggered item indicates estimate.

CAA ANNUAL MEETING

A last call for papers has been issued regarding the Annual Meeting of the Canadian Acoustical Association in Montreal, October 22-23, 1980.

o Abstracts for all papers on all aspects of acoustics will be accepted for review until September 30th. However, later submissions may be possible upon confirmation by phone from Cameron Sherry, Domtar Inc., 2001 University Street, Montreal H3A 2A6, Tel: (514) 282-5306.

o Late registration is still possible by getting directly in touch with C. W. Bradley. Hotel reservations should also be made directly to the Hotel Constellation, 3407 Peel St., Montreal H3A 1W7, Tel: (514) 845-1231 (collect).

o For further information and registration details contact: C. W. Bradley, William Bradley & Associates, 3550 Ridgewood Ave., Montreal, H3V 1C2, Tel: (514) 735-3846.

NOMINATIONS FOR CAA OFFICERS

The bylaws of the Canadian Acoustical Association require that the past-president nominate persons to fill vacancies that occur on the Board of Directors and Officers of the Association.

At the October meeting in Montreal, Bill Bradley has advised us that he will make the following nominations:

President: Tom Northwood (continuing)
Executive Secretary: John Manuel (continuing)
Editor: Deirdre Benwell
Treasurer: Les Russell (continuing)

Directors: The terms of two of our directors, Hugh Jones and Gary Faulkner, expire this year. To replace them, Stuart Eaton (Workers' Compensation Board, Vancouver) and John Foreman (University of Western Ontario) will be nominated to serve for a four year period.

Further nominations are invited and should be in the hands of the Executive Secretary, together with the consent of the nominees to serve, prior to the Montreal meeting.

TORONTO CHAPTER ANNOUNCEMENT

Dr. Theodore J. Schultz will address the CAA Toronto Chapter on "The Acoustics of the New Massey Hall" at the Auditorium of the Ontario Hydro Headquarters Bldg., Monday, September 29th.

Additional information about the project will be presented by Mr. K. Loffler, Director of the Toronto Office, Arthur Erickson, Ass. Architects. Although not yet confirmed, Dr. Elmer Isler, Director of the Toronto Mendelssohn Choir, will also give the inside story on music people's expectations in regard to concert hall acoustics.

For further information, please contact Alberto Behar at (416) 683-7516.

NOISE IN OLDER CALGARY RESIDENCES

The University of Calgary has published a "Noise Study on Older Residential Property" by T. G. Lee and H. W. Jones.

The authors tested the effectiveness of retrofitting noise control features into a 50-year old residence. The first such feature was attic insulation, the second additional window glazing, and the third a second wall structure. The authors' intention was to test ways in which older residences near city centres can be kept attractive to their occupants, who often vacate in order to escape high interior noise levels.

The report is available for $5.00 (plus $1.00 mailing) from The City of Calgary, Planning Information Centre, P. O. Box 2100, Calgary, Alberta T2P 2M5, or phone (403) 268-5360.

NEW RESEARCH CONTRACTS

To Memorial University of Newfoundland, St. John's (Drs. M. J. Clouter and H. Kiefte), $20,305 for "Acoustic properties of methane hydrate by brillouin spectroscopy." Awarded by the Dept. of Energy, Mines and Resource.

To University of Victoria, B. C. (Dr. W. M. Barss), $49,997 for "Model study of the effects of source motion on acoustic signals scattered by a rough surface." Awarded by the Dept. of National Defence.

To University of Western Ontario, London, $29,700 for "Characterization of vehicle noise radiation." Awarded by the Dept. of Transport.

To University of Victoria, B. C. (Dr. H. J. Warkentyne), $97,505 for "Research and development of a computerized automatic Speaker Identification System." Awarded by the Royal Canadian Mounted Police.

o To Pratt and Whitney Aircraft of Canada Ltd., Longueuil, Quebec, $455,764 for "Investigatory study of turbine engine exhaust noise." Awarded by the National Research Council.

LETTERS...

ACOUSTICAL CONSULTANT REGISTRATION

● From the consumer's point of view, I support Stuart Eaton's call for some form of accreditation for acoustical consultants. Planners must frequently hire consultants in disciplines such as acoustics, about which we are relatively ignorant. The establishment of a benchmark standard such as accreditation would ease the search for the right firm.

The Ontario Ministry of Transportation and Communications has occasion to use acoustical consultants on a regular basis. Our projects normally involve ambient noise measurements, prediction of noise levels following highway construction and possibly, assessment of the impact of increased noise levels on adjacent communities. The professional merit of this work may have to be defended before the Environmental Assessment Board.

We would like to compile a roster of consulting firms interested in performing this type of work for circulation to our regional offices. Any qualifying firms wishing to be included in this roster are invited to submit a prospectus to the following address: J. O'Grady, M.T.C., Environmental Office, East Building, 1201 Wilson Ave., Downsview, Ontario M3M 1J8.

J. O'Grady
Ministry of Transportation and Communications,
Downsview, Ontario.

● The letter from Stuart Eaton which appeared in Vol. 8, No. 3, raised the question of accreditation of acoustics consultants by C.A.A. This is not possible by C.A.A. at the moment as our letters patent read in part:

"The objects of the Corporation are:

(a) The fostering of a high standard of scientific, engineering and medical endeavour in all the branches of acoustics in Canada

(b) the encouragement of liaison between individuals, governments, and other organisations engaged in activities relating to acoustics and

(c) the dissemination of knowledge relating to acoustics and its applications.

"It is not the purpose of the Association to seek to establish the professional status of its members, believing this is the concern of other organisations.

"It may, however, give special recognition or awards to individuals who, in the opinion of the Board of Directors of the Association, are particularly meritorious."

Our letters patent could probably be changed within a delay of six months and an expense of about $500.00, but a more fundamental question is that of accreditation nationwide.

We will need expert legal advice regarding provincial vs. national accreditation if we are to pursue this any further.

C. W. Bradley, Eng.
William Bradley & Associates
Montreal, Quebec

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AN INVITATION

You are cordially invited to visit our hospitality suite in the Constellation Hotel during the C.A.A. annual meeting.

Our suite will be open commencing the evening of October 21st until noon October 23rd. This will give you an opportunity to relax in a convivial atmosphere and enjoy good company with friends and associates from coast to coast.

We will have available a range of new instruments including:

FROM METROSONICS:

The all new dB-603 sound level analyzer with its unique real time detector.

The dB-652 portable battery operated Metroreader.

FROM RION:

Impulse precision sound level meters, filters and level recorders.

RION manufactures a very comprehensive line of acoustic and vibration instrumentation at VERY attractive prices.

FROM IVIE:

Hand held battery operated 1/1 octave and 1/3 octave Real Time Analyzer with microprocessor based IE-17A analyzer with read out to oscilloscope or X-Y plotter.

BREN BROWNLEE
PRESIDENT
LEQ MEASUREMENTS LIMITED

PROPAGATION DU SON SUR LES SURFACES ENNEIGEES

J. Nicolas
Université de Sherbrooke
Sherbrooke, Qué.

J. E. Piercy
Conseil national de recherches
Ottawa, Ont.

D. M. Truong
Université de Sherbrooke
Sherbrooke, Qué.

INTRODUCTION

Prédire comment le son se propage d'un émetteur à un récepteur n'est pas chose facile. A l'extérieur, été comme hiver, on doit effectuer des essais selon des normes qui ne tiennent presque jamais compte de la surface réfléchissante entre la source et le micro de mesure. Des données sont disponibles sur l'effet de surfaces telles que la pelouse ou l'asphalte (1), mais très peu ou pas en ce qui a trait aux surfaces enneigées. Cette étude aborde les aspects modélisation mathématiques et mesures expérimentales de l'effet de la neige sur la propagation sonore. Il en ressort que, sous certaines conditions, on peut prédire avec assez d'exactitude l'effet de la neige sur la transmission sonore.

THEORIE

La littérature montre une évolution constante au cours des vingt dernières années afin d'inclure tous les paramètres nécessaires à la description du phénomène de propagation à l'extérieur. C'est ainsi que les phénomènes d'interférence, de diffraction, de dispersion, d'effet de sol, d'absorption moléculaire, de vent, de température ont été étudiés. Récemment T. Embleton et J. Piercy ont montré que avec un seul paramètre, l'imperméabilité à l'air, on pouvait modéliser la propagation sonore sur les surfaces extérieures à épaisseur infinie. Avec la neige, le problème est différent puisqu'il faut tenir compte de l'épaisseur finie de la couche et l'impédance a été corrigée en conséquence.

MONTAGE EXPERIMENTAL

Une source ponctuelle à niveau régularisé sert d'émetteur et un micro placé avec la configuration géométrique voulue sert de récepteur. La neige absorbant particulièrement les basses fréquences, il a fallu développer une source puissante afin d'éviter l'interférence du bruit de fond. La directionalité a été améliorée avec le calcul et la réalisation d'un cône exponentiel.

RESULTATS

Les résultats expérimentaux montrent une très bonne corrélation avec le modèle théorique pour des conditions de neige standard. L'effet du type de sol sous la couche de neige s'avère négligeable; par contre, la présence d'une mince couche de glace perturbe grandement les résultats. La neige a montré des "flow resistivity" variant de 5 à 60 C.G.S. rayls/cm selon les conditions. Il nous a également été permis de conclure que lorsque l'épaisseur atteint 8 pouces à 10 pouces, la couche peut être considérée comme infinie.

APPLICATIONS

Ces prédictions peuvent s'avérer fort utiles pour tous ceux qui doivent mesurer des véhicules (motoneiges ou autres) en hiver. Elles confirment également l'importance que l'on doit accorder aux surfaces réfléchissantes pour mesure des bruits extérieurs et lors du calcul des écrans anti-son. Elles permettent de prédire ce qui se passera l'été avec des mesures prises en hiver et vice versa.

REMERCIEMENTS

Nous tenons à remercier la section d'acoustique physique du Conseil national de la recherche à Ottawa pour sa très précieuse contribution.

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(1) "Excess attenuation or impedance of common ground surface characterized by flow resistance", J.A.S.A. spring meeting, BOSTON 1979.

VIBRATION REDUCTION OF VERTICAL PUMPS
A CASE HISTORY

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ABSTRACT

Vertical pumps are susceptible to vibration problems partly due to their "one-point" attachment to the foundation. A case history of high vibrations of a vertical pump and a design modification to remedy it are presented here. Vibration measurements were carried out to identify the causes for the high, unacceptable vibration levels and to assess the effectiveness of the proposed design modification.

Introduction

Vertical pumps of the turbine type have wide applications in the industry. They offer good economics: efficient space utilization - especially for large fluid handling capacities, simplified piping and adaptation to meet underground (low suction heads) or submerged pumping requirements.

However, vibrational behaviour of such pumps is sometimes objectionable or totally unacceptable for certain applications [1]. The fact that vertical pumps exhibit usually higher vibration levels than that of horizontal pumps can be partially attributed to how they are mounted. Vertical pumps are typically attached to the foundation at one point only, normally at ground level. Thus, creating a cantilever effect above and below the attaching point. Moreover, pump base has to support the driving motor weight. It seems that vibrations below pump base are not noted by the user nor do they tend to damage the pumpset, but that of components above foundation level are of concern, specifically motor top which is the uppermost component. Figure 1 shows an example of a vertical pump and its main components.

In power generating stations, especially nuclear ones, a high standard of equipment reliability and performance are required in order to prevent any costly, forced outage. Consequently, pumpsets used in generating stations have to meet some vibration standard. Typical vibration standards adopted are either field specific [2] or general machine oriented [3].

In this case history, preliminary vibration testing of a 4 stage, vertical pump having water lubricated bearings and driven by a 588 kW electric motor through a rigid coupling, operating at 1200 rpm, revealed excessive vibration levels accompanied by premature wear of rotating and stationary pump parts.

Vibration Measurements

Under typical operating conditions a series of vibration measurements were carried out on the pumpset in two planes: parallel to discharge head and 90° from it. Several measuring points were chosen: (a) motor at top bearing housing, (b) pump at mounting flange, (c) motor at bottom bearing housing, and (d) pump bottom (can). Identification of these points is given in Figure 2. Frequency analysis was performed to detect major amplitude components in the frequency range 0-50 Hz. In addition, impact tests were carried out to determine pumpset natural peak resonance(s) for three cases: (a) motor, (b) pump and (c) pump and motor as one unit.

Results Interpretation and Design Modification

Displacement measurements at motor top were found to be quite high: 10 and 6 mils peak-to-peak, unfiltered, parallel to pump discharge head and 90° from it, respectively. Typical maximum acceptable levels for such pumpset are 3-4 mils. Frequency spectra indicated that most of the vibration occurred at a frequency corresponding to 1/2 running speed (10 Hz).

Impact tests for the pumpset (pump and motor) at motor top showed a structural resonance around the same frequency range (10-12 Hz) - see Figure 3.

In addition, analytical simulation of pumpset bearing-rotor system using computer programs [4] identified a rotor lateral vibration mode in the range 650-670 rpm, which corresponds to 10.8-11.2 Hz.

Based on the aforementioned measurements and analysis, it was decided to try to shift the pumpset structural resonance away from 10 Hz. To achieve such a shift, a flexible plate, made of steel, was introduced between the pump head and the motor. The flexible plate is shown in Figure 4. It separates motor vibration from pump vibration by allowing each of its halves to vibrate vertically in some independent fashion; thus changing the frequency at which natural resonance of the system occurs.

Vibration levels before and after the use of the flexible plate are given in Table 1; they include displacement amplitudes filtered at frequencies corresponding to 1/2 and full running speeds as well as unfiltered overall levels. The results in the table indicate that the use of the flexible plate resulted in an appreciable reduction in vibration levels at the critical point of motor top. Most of this reduction occurred at 10 Hz. The overall vibration levels at the motor top after the introduction of the flexible plate were 3 and 1.7 mils peak-to-peak, unfiltered, as opposed to the before levels of 10 and 6 mils, parallel to the discharge head and 90° from it, respectively. Frequency spectra of impact tests and vibration measurements, again at motor top, after using the flexible plate are given in Figure 5. Impact tests' frequency spectra indicate that the aforementioned pumpset structural resonance occurring in the frequency range 9-12 Hz, have been successfully shifted to the 7-8 Hz frequency range, after the use of the flexible plate.

Conclusion

The use of a flexible plate, introduced between a vertical pump head and the driving motor, has produced an appreciable reduction in motor top vibration levels. This reduction is attributed to a shift in the pumpset natural structural resonance away from the critical frequency of 1/2 running speed.

References

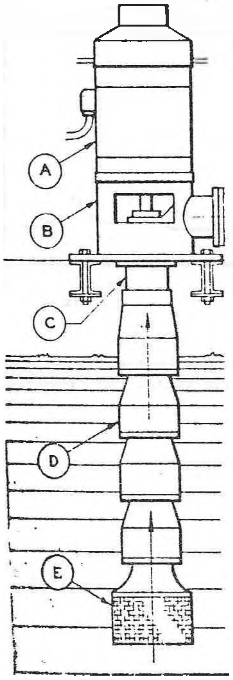
1. A. Kovats, "Vibration of vertical pumps," Journal of Engineering for Power, April 1962, pp 195-203.

2. API Standard 610, "Centrifugal pumps for general refinery services," Fifth Edition, March 1971, American Petroleum Institute, Division of Refining, 1801 K Street, N.W., Washington DC 20006.

3. ISO 3945, "Mechanical vibration of large rotating machines with speed range from 10 to 200 rev/s - Measurement and evaluation of vibration in situ", Ref No ISO 3945-1977 (E).

4. D.F. Li and E.J. Gunter, "Linear stability analysis of dual-rotor systems - A manual for use with computer program STAB2V2", Report No UVA/528140/MAE78/113, Research Laboratories for the Engineering Sciences, School of Engineering and Applied Science, University of Virginia, 1978.

5. R.J. Fritz, "The effects of an annular fluid on the vibrations of a long rotor, Part 1 - Theory and Part 2 - Test", Journal of Engineering for Industry, December 1971.



A ELECTRIC MOTORS
B DISCHARGE HEAD
C DISCHARGE COLUMN
D TURBINE PUMP BOWL ASSEMBLY
E SUCTION STRAINER

Figure 1. Typical Vertical Pump Components

Table 1. Vibration levels with and without flexible plate. For measurement point identification, see Figure 2.

Measurement Point	Vibration Level, p-p mils					
	10 Hz (1/2 running speed)		20 Hz (running speed)		Overall level unfiltered	
	Without plate	With plate	Without plate	With plate	Without plate	With plate
Motor top:						
A	7	0.5	0.6	0.4	10	3
B	4.6	--	0.4	0.4	6	1.7
Motor bottom:						
C	1.3	--	0.6	1.5	3	4.8
D	1.7	--	0.4	1.8	5	4
Pump head:						
E	1.8	--	0.6	1.8	5	5
F	0.6	--	0.3	0.6	1.5	2.5
Pump bottom:						
G	1.2	--	4.4	3.0	7	4
H	--	--	5.2	3.4	7.5	5

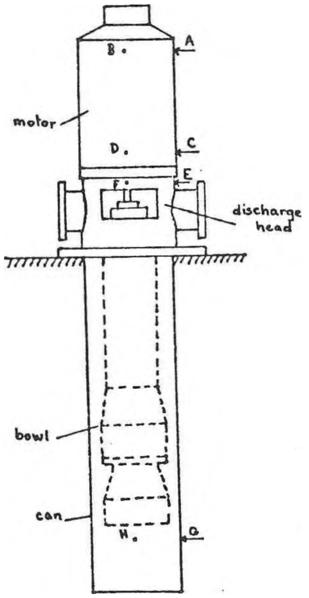


Figure 2. Vibration Measurement Points.
Given points identification is used in Table 1.

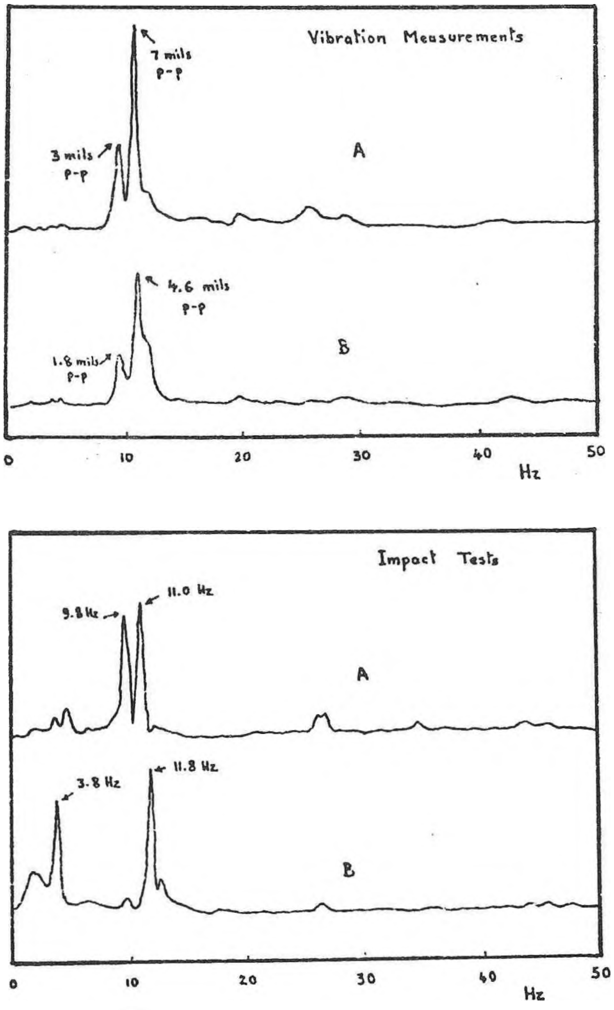


Figure 3. Frequency spectra of vibration measurements and impact tests at motor top. A: parallel to discharge head; B: 90° from discharge head.

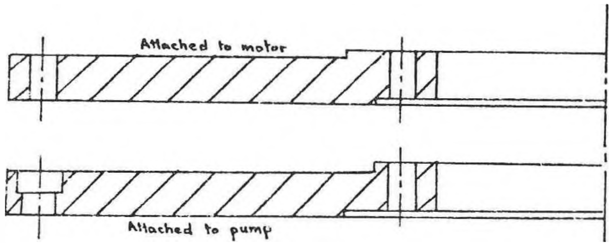


Figure 4. Details of flexible plate.

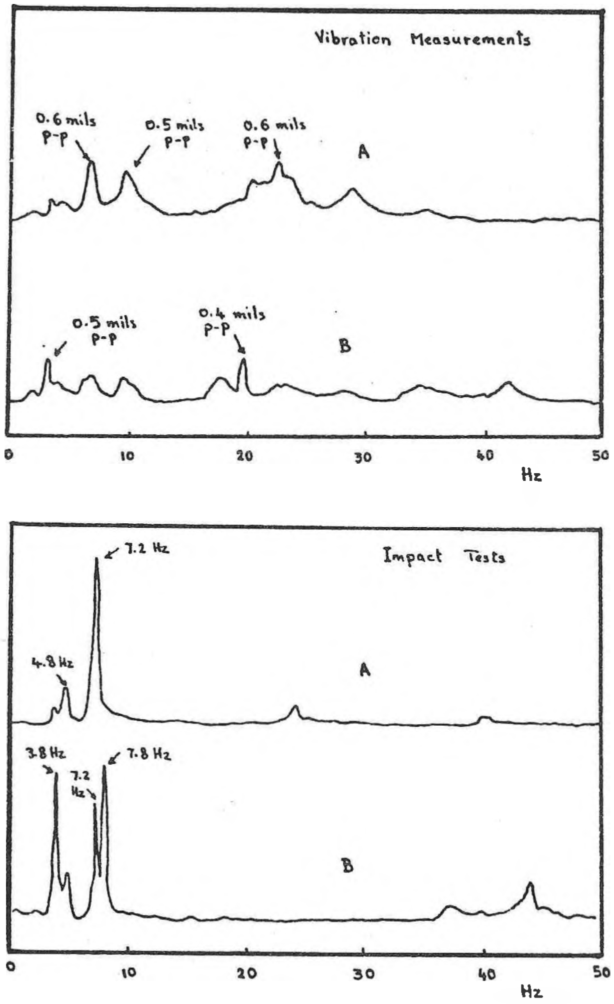


Figure 5. Frequency spectra of vibration measurements and impact tests at motor top after installation of flexible plate. A: parallel to discharge; B: 90° from discharge head.

This paper was presented at the Vehicle Noise Regulation and Reduction Session of the Society of Automotive Engineers' Congress and Exposition, Detroit, February 1980, and is reproduced here by permission of the Society.

800278

Noise Exposure of Truck Drivers

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THIS PAPER PROVIDES DETAILS of a study undertaken to determine the magnitude of the noise exposure of truck drivers running heavy vehicles under commercial operating conditions. Since a number of standard procedures have been developed for in-cab noise measurements,the relationship between these measurements and the noise exposure of the driver has been investigated. Also, an effort was made to identify and quantify various noise sources which contribute to the drivers' exposure during normal operations.

The evaluation of the driver's noise exposure from in-cab noise measurements with standard procedures does not take into account variations in vehicle operation, tire and aerodynamic noise. Additional errors are introduced by placing the microphone at some prescribed distance from the ear, since in that region the sound field can vary significantly. These errors are only partially reduced by the use of noise dose meters.

In this investigation a specially developed, continuously recording instrument is used for measuring the noise exposure of drivers. It is equipped with a sub-miniature microphone which can be easily placed in the cavum of the concha. In previous studies it was shown that the measurement of the sound pressure level at this point was least influenced by extraneous effects.

GENERAL CONSIDERATIONS

The evaluation of exposure from noise measurements requires integration with respect to time and in accordance with the relationship defined by a particular hearing conservation criterion or regulation. If the noise level is relatively constant, the exposure can be evaluated by approximate integration using sound level meter measurements.

In most applications, however, owing to variations of noise level and movement of the subject, continuous measurement, integration and updating storage are required. Those functions are effectively performed by noise dose meters and several models are now commercially available. The information provided by these instruments is generally restricted only to the numerical

ABSTRACT

The noise exposure of truck drivers was measured during normal commercial payload runs with special instruments, which are equipped with subminiature microphones. These can be mounted within the cavum of the concha, where measurements are least affected by extraneous effects.

By means of these instruments sound levels were continuously recorded within both ears of the driver and at the centre of the cab. Analysis of results shows that the driver's exposure is highest during freeway hauls and that permanent hearing loss hazard may exist. Frequent use of radio or CB radio can significantly increase this hazard. It is also evident that the sound levels measured within the ears of the driver are generally significantly higher than at the centre of the cab.

SAE/SP-80/456/$02.50

value of the noise dose relative to a particular noise regulation or criterion.

Under certain measuring conditions significant errors may arise due to the location of the microphone on the subject's body. When used in industrial situations, in broadband and diffuse sound fields, these errors are generally relatively small and have a negligible effect on the exposure measurement (1)*.

In the presence of dominant discrete frequency components large measuring errors can result from body reflections and shielding. Under these conditions the location of the microphone on the body, the relative positions of the noise sources and their spectral content have significant influence (2,3). Even placing the microphone near the ear does not offer an acceptable improvement. The use of appropriate transfer functions for eliminating the undesirable extraneous influences is, in addition to being very laborious, almost impossible in practice owing to difficulties in determining some of the governing variables. The simplest and most effective solution is to select a measuring location at which the influence of these factors becomes negligibly small. Brammer and Piercy (4) have shown that the cavum of the concha is such a location. This reading can also be relatively easily converted to the sound level at the ear drum, since the corresponding transfer function is independent of the extraneous variables.

The sound field within the truck cab is complex. The main contributors are engine, exhaust, intake, fan, aerodynamic, tire and road noise. The noise transmission is partly airborne and partly structure borne and it is influenced by the construction and shape of the cab. The sound field itself is dominated by discrete frequency components. Spatial variations of the sound level will thus exist in the cab and will change with operating conditions. Results obtained in a previous investigation (5) display the non-uniform and unpredictable distribution of noise levels in truck cabs. Since it is practically impossible to predict or control such variations, the ideal solution is to select a microphone location for exposure measurements at which the influence of these variables is smallest. The cavum of the concha satisfies this requirement.

Therefore the basic operator exposure and cab noise measurements were made using the "Ear Bug" unit. This instrument, which was originally developed by the Acoustics Section, Division of Physics, National Research Council of Canada, consists of a subminiature microphone coupled to a modified commercial cassette tape recorder. The system is small and light and can be carried without impediment of normal activities. The microphone can be attached anywhere on the subject and, what is perhaps more important, it is sufficiently small to be placed in the cavum of the concha. A complete temporal record of the A-weighted sound level at the microphone position is available from the cassette tape and can be further analyzed to provide any required information.

PROCEDURE

All 58 tested vehicles were supplied by commercial fleet operators. Measurements were performed during normal long distance payload runs. For economic reasons the choice of vehicles, routes and operating conditions was restricted to routine availability. The type of road over which the vehicle travelled was considered to be the operating variable of greatest significance. Each test run was selected to be predominantly of one type i.e. city, highway or freeway. In cases of combined trips, recordings for each road type were analyzed separately.

The driver was always accompanied by a technician who continuously logged operating and weather conditions and monitored instrumentation. Calibration procedures were carried out on relevant instrumentation and calibration signals were recorded on all magnetic tapes.

For the initial series of tests the noise exposure of the driver was recorded only at his right ear. The microphone was placed within the cavum of the concha near the entrance to the ear canal. To obtain worst noise conditions the window on the driver's side was fully opened. It was expected that noise levels at the left ear, which was nearer to the open window, would be higher. However, owing to the possibility of wind induced turbulence at the microphone, this measuring station was not used initially for continuous recording, but only for trial measurements. Evaluation of these results, in particular the narrow band frequency analyses, showed that the turbulence effect was negligible in comparison with other contributing sources and did not influence the noise exposure

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*Numbers in parentheses designate References at end of paper measurements. Consequently, after Vehicle #17, the exposure of the driver was monitored at both ears. In addition to the measurements made at both ears of the driver, an "Ear Bug" microphone was suspended from the cab ceiling to a position 150 mm to the right of the driver's ear and at the same level with it. This will be referred to as the centre of cab position.

To obtain a measurement of the basic noise making capacity of each vehicle, in-cab noise measurements were performed in accordance with standard measuring procedures SAE J336a and CSA Z107.23. The first procedure was significantly longer than the second and required a special test site, which was not readily available for routine testing. The results obtained by both methods were very close and since for the purpose of this study CSA Z107.23 was more acceptable, the use of SAE J336a was eventually discontinued. Measurements for both procedures were taken directly with a precision sound level meter.

DISCUSSION AND RESULTS

The specifications of the 58 heavy trucks tested are shown in Table 1. It should be noted that, since the fleet vehicles provided for test runs were, on the average, relatively new and well maintained, the results must therefore be expected to be marginally weighted in favour of lower noise exposures.

The Leq values obtained for each vehicle and the corresponding CSA Z107.23 value are summarized in Table 2. During some of the test runs, owing to low temperatures, it was found necessary to either close the driver's window partially or close it completely and open the vent window. Measurements taken under these conditions are appropriately marked in this table. In addition, all test runs noted in this table were made with radios off and conversation within the cab reduced as far as possible.

Narrow band frequency spectra were obtained at the three measuring stations (left ear, right ear and centre of cab) during city, highway and freeway driving. Figure 1 shows typical results of such an analysis of the noise recorded at the right ear of a driver during a highway run. It is quite evident that the noise is dominated by discrete frequency components. This was found to be the case at all three measuring stations within the cab and for each driving condition. Also a progressive reduction of the overall sound level from the left ear to the centre of cab position was noted. This appears to be predominantly due to a distinct attenuation of frequency components above 1.5 kHz. The most likely explanation of this effect is increased absorption within the cab of high frequency sound energy and shielding of wind noise.

Table 1 - Truck Specifications

VEHICLE	YEAR	DIESEL ENGINE SPECIFICATIONS	
		CYCLE	RATED POWER
1	1975	2	235 hp - 2100 rpm
2	1971	4	320 hp - 2600 rpm
3	1973	4	310 hp - 2100 rpm
4	1973	4	310 hp - 2100 rpm
5	1971	4	310 hp - 2100 rpm
6	1975	2	210 hp - 2500 rpm
7	1974	2	310 hp - 2100 rpm
8	1968	2	185 hp - 4000 rpm
9	1975	2	235 hp - 2100 rpm
10	1974	2	310 hp - 2100rpm
11	1975	2	235 hp - 2100rpm
12	1974	4	310 hp - 2100rpm
13	1976	2	265 hp - 2150rpm
14	1972	2	235 hp - 2100rpm
15	1972	2	235 hp - 2100rpm
16	1972	2	235 hp - 2150rpm
17	1972	2	235 hp - 2150rpm
18	1976	2	265 hp - 2100rpm
19	1976	2	265 hp - 2100rpm
20	1974	2	265 hp - 2100rpm
21	1976	2	265 hp - 2100 rpm
22	1974	2	265 hp - 2100 rpm
23	1975	2	265 hp - 2100 rpm
24	1974	2	265 hp - 2100 rpm
25	1975	2	265 hp - 2100 rpm
26	1976	2	265 hp - 2100 rpm
27	1974	2	265 hp - 2100 rpm
28	1973	2	360 hp - 2100 rpm
29	1973	2	360 hp - 2100 rpm
30	1973	2	235 hp - 2100 rpm
31	1977	4	290 hp - 1900 rpm
32	1975	2	304 hp - 2000 rpm
33	1975	2	304 hp - 2100 rpm
34	1975	2	304 hp - 2100 rpm
35	1975	4	172 hp - 1900 rpm
36	1977	4	290 hp - 1900 rpm
37	1976	4	290 hp - 1900 rpm
38	1971	2	304 hp - 2100 rpm
39	1975	2	304 hp - 2100 rpm
40	1971	2	304 hp - 2100 rpm
41	1971	2	304 hp - 2100 rpm
42	1971	2	304 hp - 2100 rpm
43	1975	2	304 hp - 2100 rpm
44	1977	4	290 hp - 2100 rpm
45	1975	2	304 hp - 2100 rpm
46	1977	4	290 hp - 1900 rpm
47	1978	4	290 hp - 1900 rpm
48	1977	4	290 hp - 2100 rpm
49	1978	4	290 hp - 1900 rpm
50	1978	4	290 hp - 1900 rpm
51	1978	4	290 hp - 1900 rpm
52	1978	4	290 hp - 1900 rpm
53	1978	4	290 hp - 1900 rpm
54	1978	4	290 hp - 1900 rpm
55	1975	2	304 hp - 2100 rpm
56	1976	2	228 hp - 2100 rpm
57	1977	2	228 hp - 2100 rpm
58	1976	2	228 hp - 2100 rpm

During initial measuring runs it was observed that to be heard and be intelligible, levels of speech, radio and CB radio had to be set several decibels above the environmental noise level. Typical examples are shown in Figure 2 and Figure 3. It is interesting to note

Table 2 - Summary of Noise Measurements

VEHICLE	L_{eq}(CITY) - dBA			L_{eq}(HIGHWAY) - dBA			L_{eq}(FREEWAY) - dBA			CSA STANDARD Z 107.23
	MICROPHONE POSITION			MICROPHONE POSITION			MICROPHONE POSITION			
	LEFT EAR	RIGHT EAR	CAB	LEFT EAR	RIGHT EAR	CAB	LEFT EAR	RIGHT EAR	CAB	
1	-	85	83	-	85	83	-	89	90	81
2	-	-	-	-	-	-	-	90	91	85
3	-	86	84	-	-	-	-	88	84	80
4	-	-	-	-	-	-	-	87	87	88
5	-	82	82	-	-	-	-	-	-	-
6	-	86	84	-	-	-	-	-	-	83
7	-	85	84	-	85	-	-	87	86	82
8	-	82	83	-	-	-	-	87	86	80
9	-	-	-	-	-	-	-	-	87	81
10	-	89	-	-	-	-	-	89	88	86
11	-	-	-	-	-	-	-	91	86	83
12	-	-	-	-	-	-	-	88	-	85
13	-	83	83	-	87	84	-	88	86	82
14	-	-	-	91	87	88	-	-	-	91
15	-	-	-	-	87	89	-	-	-	84
16	-	-	-	-	90	87	-	-	-	89
17	-	-	-	-	87	87	-	-	-	85
18	83	81	80	-	86	84	87▲	86	85	82
19	90	86	85	-	-	-	90	87	86	86
20	84	81	80	86	83	83	87▲	86	84	81
21	-	-	-	-	-	-	91▲	90	88	89
22	84	82	80	85	83	81	88	86	83	81
23	86	86	86	87	88	86	89▲▲	90	86	87
24	83	82	81	84	83	81	88	85	83	81
25	84	83	81	86	85	83	87▲	87	85	83
26	-	82	-	87	84	81	89	85	82	83
27	90	88	88	-	-	-	92	90	90	88
28	87	89	88	-	-	-	-	-	-	86
29	-	87	86	-	-	-	-	-	-	88
30	88	89	90	-	-	-	-	-	-	91
31	90	89	87	92	90	88	96	90	90	87
32	90	90	89	91	90	88	93	91	90	88
33	-	-	-	-	-	-	91▲	91	90	90
34	-	91	90	-	93	91	92▲▲	94	91	90
35	90	91	91	91	91	91	91▲▲	94	90	93
36	-	-	-	-	-	-	89▲▲	91	88	86
37	89	87	86	-	-	-	92	91	89	87
38	92	88	87	91	90	89	94	90	89	87
39	-	-	-	88▲▲	89	86	88▲▲	90	85	87
40	88▲▲	86	86	89▲▲	90	88	89▲▲	90	87	87
41	89	88	86	-	-	-	89▲	89	85	87
42	90	90	88	-	-	-	91▲	91	89	88
43	88▲▲	91	89	89▲▲	89	88	90▲▲	94	90	87
44	-	-	-	-	-	-	87	88	87	86
45	-	-	-	92	91	90	93	91	91	86
46	-	84	83	-	86	86	90	88	88	84
47	-	83	81	-	-	-	88	88	85	84
48	-	-	-	-	-	-	91	-	87	86
49	-	-	-	-	-	-	92	-	88	83
50	-	-	-	-	-	-	-	86	88	82
51	-	-	85	-	-	-	-	89	88	84
52	-	-	-	-	-	-	87	87	86	84
53	-	88	-	-	-	-	91	88	87	82
54	88	-	85	-	-	-	89	-	87	84
55	89	86	85	-	-	-	90	88	86	86
56	85	88	84	87	88	87	-	-	-	85
57	-	-	91	-	-	92	-	-	-	88
58	85	84	81	88	87	86	-	-	-	82

▲ WINDOWS PARTIALLY OPEN
▲▲ WINDOWS CLOSED - WINDOW VENT OPEN

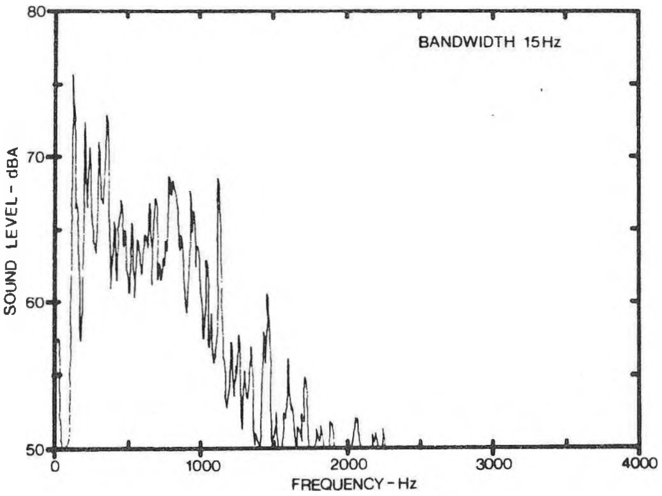


Fig. 1 - Frequency analysis of highway driving monitored at right (inner) ear

that the use of a CB radio resulted in increases in instantaneous sound level of up to 10 dB. The influence on the driver's noise exposure depends, in addition to sound levels, also upon the duration of use and location of the source. The combined effect is adequately defined by the energy equivalent level, Leq, at the reception point. Recordings were taken on several vehicles at all three measuring stations during freeway runs at a steady 100 km/h, with normal use of CB radio and without it. The results are shown in Table 3. It can be seen that this effect is highest at the centre of cab position and lowest at the left ear. At the right ear an average increase in Leq of 2.7 dB was measured, which will increase the Noise Exposure Rating by approximately 50%.

With reference to the Leq values shown in Table 2, it can be seen that they depend upon the measuring location and their magnitudes increase in the order: CSA standard procedure, centre of cab, right ear and left ear. These increases and overall values of Leq are lowest for city driving and highest for freeway hauls. The average value of the Leq difference between freeway and city driving, measured at the right ear, is 2.9 dB with a standard deviation of 1.6 dB. Although these results are not completely consistent, which appears to be primarily due to the inherent non-uniformity of the sound field in the cab, a definite trend is quite evident.

Figure 4 indicates both the variation in the Leq value for each of the three driving conditions and the corresponding sound level distributions obtained for a particular vehicle.

For freeway driving, the sound level at the left ear is on the average 5.7 dB higher than that measured with the CSA standard procedure. This suggests that any method of determining noise exposure which is based on measurement of sound level at some distance from the subject's ear, may results in significant underestimate. Errors in excess of 100% appear to be quite possible.

Correlations between data for the right ear, left ear and centre of cab positions, for each of the three driving conditions, were also determined. The results of two such correlations are shown in Figure 5 and Figure 6. In these graphs, r represents the correlation coefficient and σ the standard deviation. Generally, the best correlation exists between the right ear and centre of cab with the value of correlation coefficient highest for city

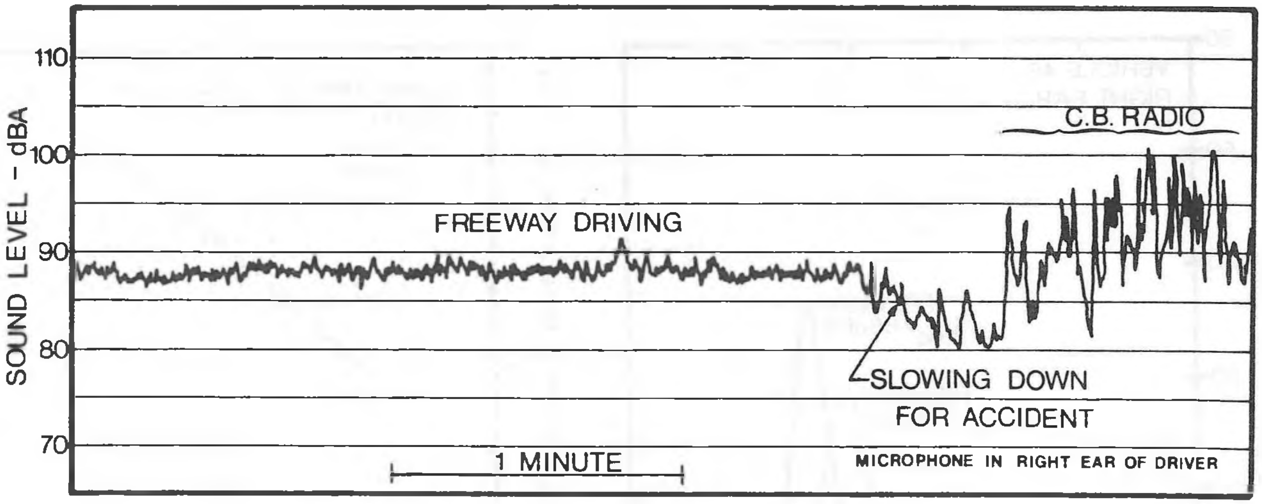
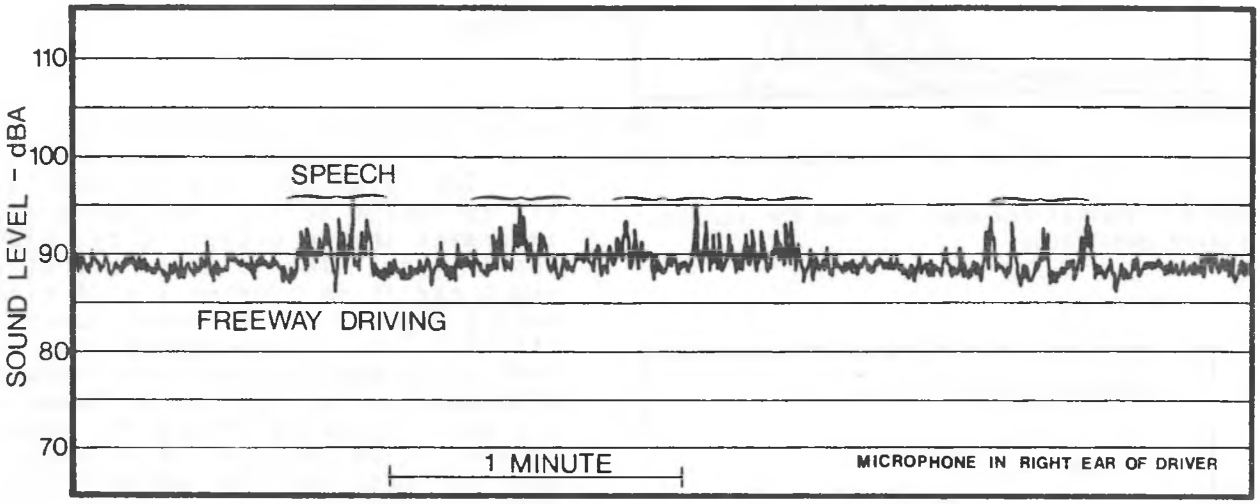


Fig. 2 - Vehicle #53: effect of CB radio on noise levels



Fiq. 3 - Vehicle #48: effect of speech on noise levels

Table 3 - Effect of CB Radio on Values of L_{eq}

VEHICLE	CSA STANDARD Z107.23 dBA	LEFT EAR - dBA		RELATIVE EFFECT dBA	RIGHT EAR - dBA		RELATIVE EFFECT dBA	CENTRE CAB - dBA		RELATIVE EFFECT dBA
		NO CB	WITH CB		NO CB	WITH CB		NO CB	WITH CB	
31	87	96	99	+3	-	-	-	90	95	+5
33	90	91	97	+6	95	98	+3	91	95	+4
34	90	92	92	0	94	97	+3	91	94	+3
36	86	89	91	+2	91	96	+5	88	91	+3
37	87	91	91	0	93	94	+1	89	92	+2
38	87	94	94	0	90	91	+1	89	91	+3
40	87	-	-	-	-	-	-	85	88	+3
41	87	89	91	+2	89	92	+3	-	-	-

driving and lowest for freeway driving. The results also indicate the highest noise levels exist at the left ear.

CONCLUSIONS

Under most operating conditions the sound field inside the cab is dominated by discrete frequency components. This suggests that the location of the microphone may have significant influence on measurements. For accurate determination of noise exposure the microphone should be placed within the cavum of the concha.

The use in the cab of radio or CB radio can significantly increase the noise exposure of the driver. Tests performed on a sample of 8 vehicles show that normal use of CB radio increases the value of Leq at the right ear by an average of 2.7 dB. This corresponds to an increase on the noise dose of at least 50%. It can thus be a significant contributor to the over-

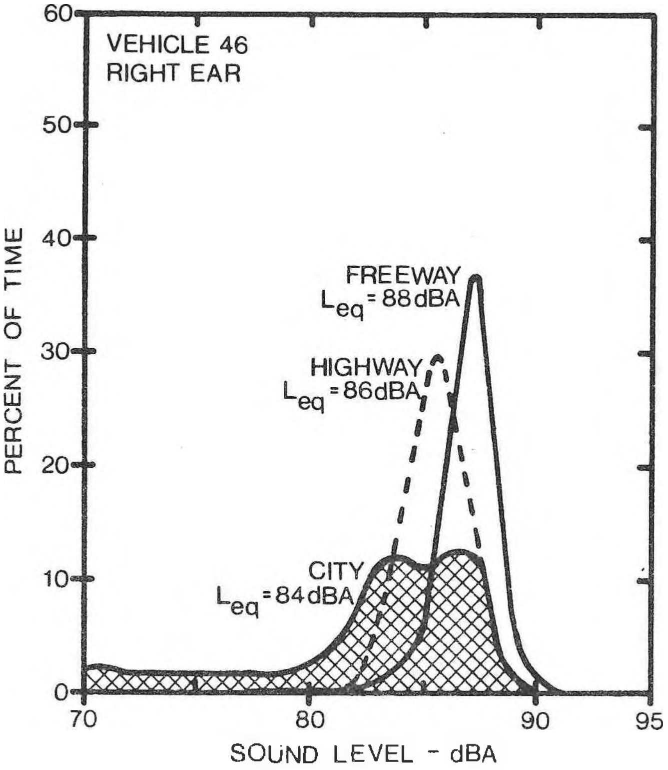


Fig. 4 - Statistical distribution for various driving conditions

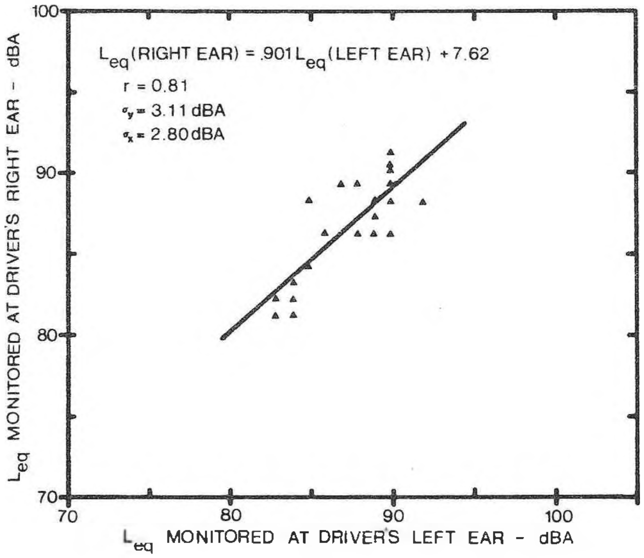


Fig. 5 - Comparison of sound levels for city driving

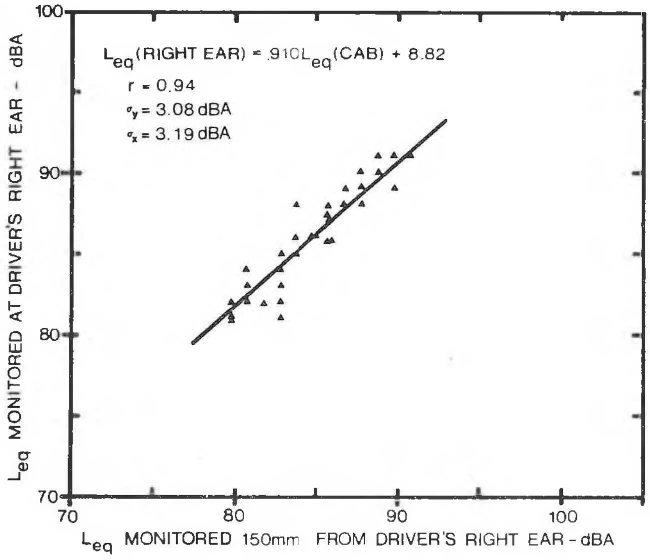


Fig. 6 - Comparison of sound levels for city driving

all noise exposure.

The sound levels measured at the centre of cab position, right and left ear of the driver, increase generally in that order. The value of the Leq at the left ear is on average 6 dB higher than that at the centre of cab position, which is the measuring station used for standard procedures.

The noise exposure of truck drivers is lowest during city driving and increases in the order: city, highway and freeway. The value of Leq at the right ear is on average 1.5 dB higher during highway driving than during city driving. The corresponding comparison between highway and freeway driving shows an average difference of 1.6 dB. The value of Leq for freeway driving is an average 2.9 dB higher than for city driving, which is approximately equivalent to an increase of noise exposure of 50%.

ACKNOWLEDGEMENT

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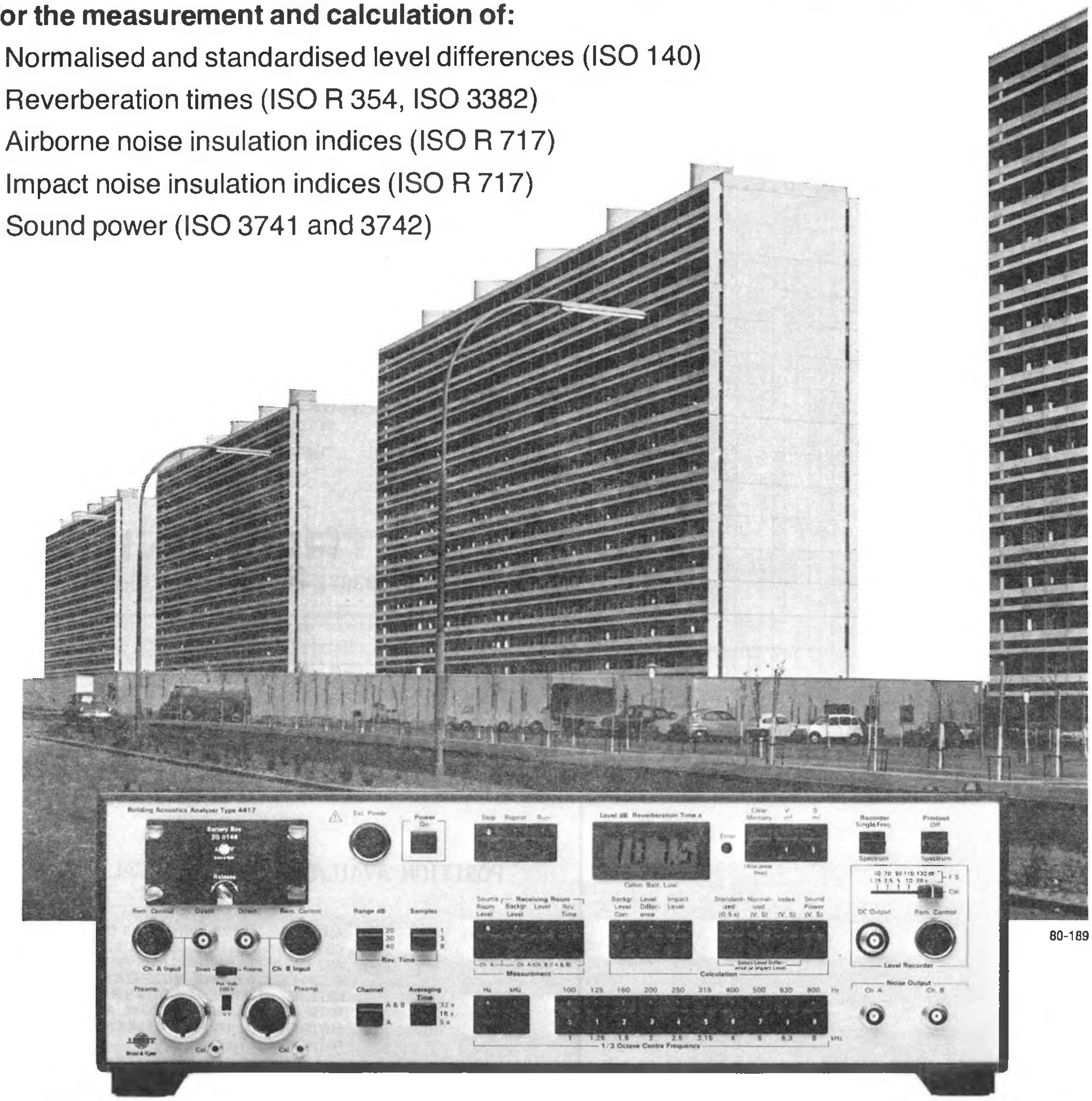

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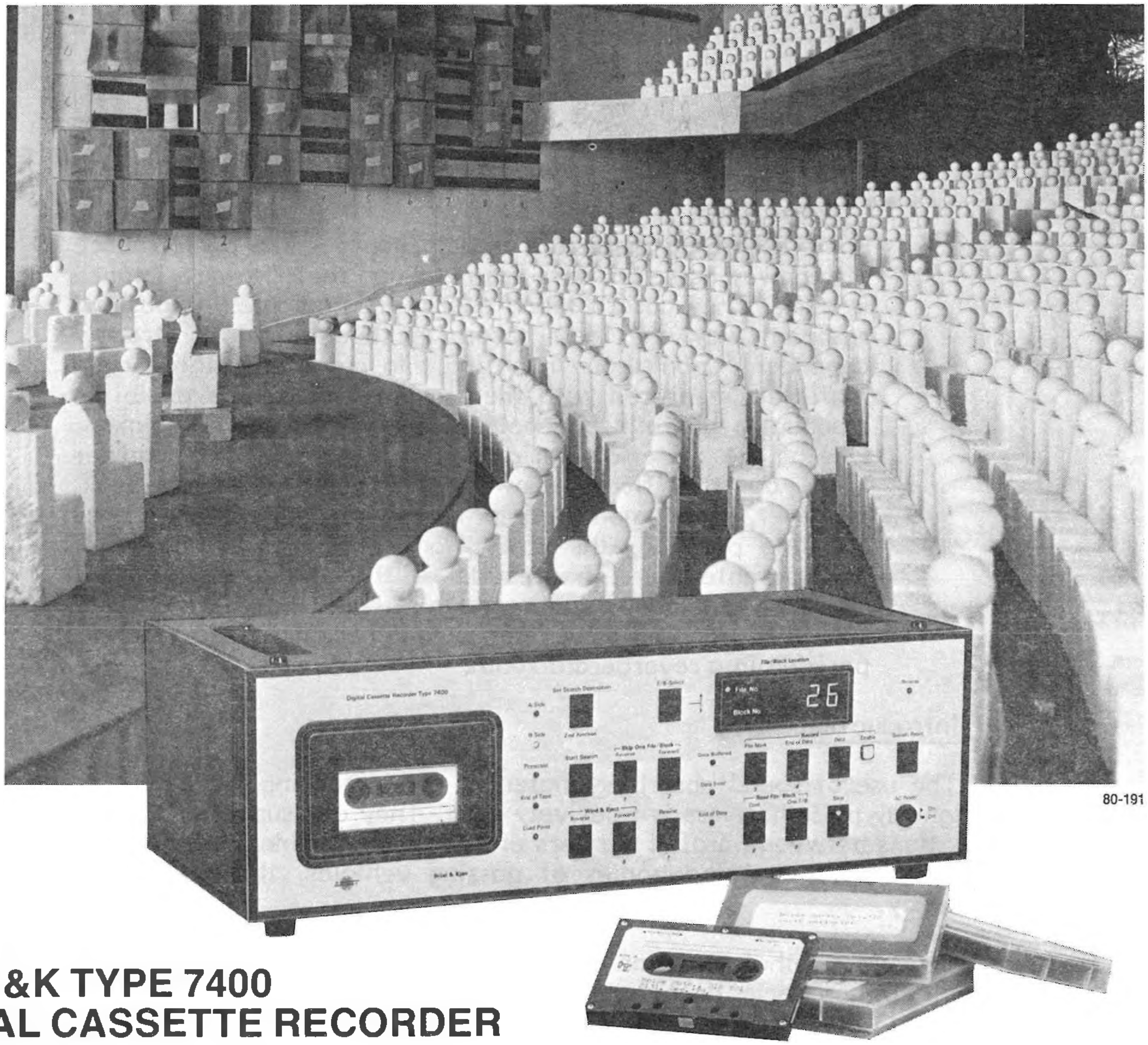

80-191

LIMITATIONS IN THE MEASUREMENT OF THE SOUND ABSORPTION COEFFICIENT ON MATERIALS FOR HIGHWAY NOISE BARRIERS

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ABSTRACT

Some absorbing materials used to improve the performance of highway noise barriers are rigid and their flow resistance is high. They absorb sound energy in a complex porous and resonant way and their absorption coefficient is strongly dependent upon their mounting. In our study, three rigid materials measured with the standing wave tube exhibited resonant peaks at frequencies depending on their thickness. One of the materials, measured in a reverberant chamber lying on the floor, showed the same resonant peak. However, when measured in the same chamber in a free standing position, the absorption curve was typical of a porous material. The results of the study confirm that "hard," rigid, acoustical materials should not be measured with the standing wave tube but rather in a free standing position in a reverberant room.

1. Introduction

The use of sound absorbing materials for increasing the attenuation provided by highway noise barriers is relatively new. They are supposed to reduce multiple reflections between parallel barriers erected on both sides of a highway or between a single barrier and the bodies of passing vehicles, thereby increasing barrier efficiency.

Because of their outdoor application, these materials have to endure severe adverse atmospheric agents as well as corrosive exhaust fumes from passing vehicles. They have also to withstand the mechanical and chemical actions of water, snow, ice and salt mixtures splashed from vehicle wheels. These effects are especially strong on the lower part of the barriers.

To ensure adequate durability, some commercial products are made of soft materials bonded by hard resins or portland cement into a kind of solid mass. Usually they have a relatively high density, are self-supported, and have a high flow resistance. This type of material is called a "hard" material in this paper.

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*Work performed while the author was at the Ontario Ministry of Transportation and Communications.

Since, during the measurement of sound absorption coefficient, material samples are mounted in a specific way, the resulting absorption coefficient vs frequency curves are valid only for a particular mounting, thus limiting the validity of the measurement result. This is obviously not a new concept, but should be remembered when handling data regarding these materials.

In our study,* the sound absorption coefficients of three "hard" materials used for highway noise barriers were measured with the standing wave tube (1). All results showed resonant peaks varying with the thickness of the samples. A conventional, porous sound absorbing material used as a control did exhibit the well-known, increasing-with-frequency sound absorption curve when measured in the same way.

One of the highway materials was also measured at the Division of Building Research, National Research Council, with the tube and also in the reverberation room (2). When measured lying on the floor of the room, its absorption coefficient showed the same resonant peak as when measured with the tube. But, when mounted in a free standing position, the absorption curve was typical of a porous material's, confirming the effect of the mounting.

The results of this study show that if a material is to be used as a noise barrier "by itself" (i.e., without a backing), then its sound absorption should not be measured in the standing wave tube, and if measured in a reverberant room, it should be held in a free standing position.

2. Description of the Tests

For a summary, see Table 1.

2.1 Materials

Following is the manufacturer's description of the materials measured for sound absorption.

- Durisol, from Durisol Materials Limited: Lightweight building material made of chemically mineralized and neutralized organic softwood shavings, bonded together under pressure with portland cement. Durisol is supplied as panels made of the above described absorption layer, 75 mm (3") thick, and a hard, reinforced concrete backing, 19 mm (3/4") thick. (Other configurations were also tested - see later.)

- Fiberglas AF530 from Fiberglas Canada Limited: Glass-fiber boards compressed to a controlled density, bonded by a thermosetting resin.

- Herco Type 713 from Kemlite Corporation: Porous, random textured material made of polyester resin, glass fibers, aggregate and fillers.

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*Results of the study performed on one material have been published in Reference 3.

- Petrical from Cornell Corporation: Chemically treated, long, tough, northern aspen wood fibers, bound with portland cement, moulded under pressure.

The thickness of the samples ranged from 25 to 81 mm.

2.2 Sound Absorption Measurements

The measurements were performed at two different places, using two different measuring techniques.

At the Research Laboratory, Ministry of Transportation and Communications, Ontario, the measurements were done according to the ASTM C384-77 (1) method, using standard instrumentation manufactured by Bruel and Kjaer.

At the division of Building Research, National Research Council, materials were measured according to both ASTM C384-77 (1) and ASTM C423-77 (2) methods. For the measurements in the reverberant chamber, the materials were placed in two different ways: first, lying on the floor, and then free standing in an upright position.

3. Measurement Results

The results of the measurements are shown in Table 2. They are also given in Figures 1 through 7.

The measurements performed with the impedance tube are reported in percent. The others, done in the reverberation chamber, are in Sabines. When a material was measured in the free standing position, both surfaces were used for the calculation of the absorption coefficient. The sample areas for those measurements were 8.1 m^2 (89.8 $feet^2$) for measurements no. 12 and 14, and 4.4 m^2 (48.8 $feet^2$) for no. 11 and 13.

4. Discussion

According to their surface density and general mechanical characteristics, the materials we tested can be divided into:

- Hard: Durisol, Herco and Petrical, and
- Soft: Fiberglas

The absorption curves of the first group as shown in Figures 1, 2 and 3 have peaks suggesting a mixed, porous and resonant way of sound absorption. This is obviously not the case for the Fiberglas measured as a control (see Figure 4).

The same resonant behaviour is observed in Figure 5 where results of the measurements of a "hard" material using both methods (reverberant room and standing wave tube) are shown. The resonant frequencies in both cases are the same, thus suggesting a similar membrane-like behaviour.

On the other hand, as results in Figure 6 show, as soon as the hard backing is "removed" by erecting the sample, the resonant phenomenon disappears and the material behaves in a porous-like way, similar to that shown in Figure 4.

5. Conclusions

The standing wave tube technique should not be used for the measurement of "hard" acoustically absorbent materials unless they are intended to be mounted against a wall. For the same reason, if the measurement is done in the reverberant room, the sample should be installed in a free standing way, avoiding interaction with the reverberant room floor.

The non-observance of these recommendations can lead to gross overestimates of the sound absorbing qualities of a given material.

6. Acknowledgments

Thanks are due to Dr. T. D. Northwood, Head, Noise and Vibration Section, Division of Building Research, National Research Council, for many useful discussions and to Mr. W. T. Chu from the same section for carrying out the test mentioned in Table I. Most of the tube measurements were performed by Mr. G. Giles and Mr. A. Maio from the Research Laboratory, Experimental and Demonstrating Testing Group, Ministry of Transportation and Communications, Ontario. The study was done while the author was at the Acoustics Office, Research and Development Division, of the same Ministry.

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2. ANSI/ASTM C423-77, "Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method," American National Standards Institute, 1977.

3. A. Behar and D. N. May, "The Sound Absorptive Qualities of Material 2 for Various Methods of Installation," Appendix A in "Durability of Sound Absorbing Materials for Highway Noise Barriers." J. Sound and Vib. 71, 33-54, 1980.

Table 1. Summary of Materials and Measurements.

Measurement	Material	Thickness		Density	Surface Area Density	Measurement Method	Measurement Place	Mounting	Results on Figure	Observation
No.		mm	Inches	kg/m³	kg/m²	-	-	-	-	-
1	Durisol	25	1	560	14	Tube1)	NRC3)	----	1A	Absorption layer only
2	Durisol	50	2	560	28	Tube	MTC4)	----	1B	Absorption layer only
3	Durisol	75	3	560	42	Tube	NRC	----	1C & 5B	Absorption layer only
4	Durisol	75	3	560	42	Tube	MTC	----	1D	Absorption layer only
5	Fiberglas	25	1	48	1.2	Tube	MTC	----	4	----
6	Fiberglas	50	2	48	2.4	Tube	MTC	----	4	----
7	Herco	34.2	1 3/8	658	22.5	Tube	MTC	----	2	----
8	Herco	50	2	658	33	Tube	MTC	----	2	----
9	Petrical	37.5	1 1/2	567	22	Tube	MTC	----	3	----
10	Petrical	75	3	576	43	Tube	MTC	----	3	----
11	Durisol	75	3	560	42	Rev. Cham.2	NRC	Laying5	5A & 6A	Absorption layer only
12	Durisol	75	3	560	42	Rev. Cham.	NRC	Standing	6B	Absorption layer only
13	Durisol	81.3	3 1/4		98	Rev. Cham.	NRC	Laying	7A	Complete panel
14	Durisol	81.3	3 1/4		98	Rev. Cham.	NRC	Standing	7B	Complete panel

Notes: 1) see Reference 1
2) see Reference 2
3) Division of Building Research, National Research Council, Ottawa
4) Research Laboratory, Ministry of Transportation and Communications, Ontario
5) see Reference 2, Figure 1, Number 4

Table 2. Sound Absorption Coefficients.

Measurement Number	Frequency, Hz																
	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3100	4000	5000
1	---	---	4	5	11	9	14	18	29	31	83	99	67	57	39	--	--
2	---	---	6	7	8	16	24	52	90	73	47	37	37	---	---	--	--
3	---	25	22	32	56	79	92	77	55	48	50	77	70	73	76	--	--
4	---	---	25	36	55	78	94	70	52	44	58	82	57	---	---	--	--
5	---	---	7	9	10	14	14	24	29	42	53	68	80	---	---	--	--
6	---	---	10	16	21	30	33	46	59	70	79	89	92	---	---	--	--
7	---	---	15	14	12	15	17	23	37	60	89	95	70	---	---	--	--
8	---	---	9	13	19	30	43	67	78	67	53	41	45	---	---	--	--
9	---	---	--	--	--	--	20	37	69	96	93	68	43	---	---	--	--
10	---	---	34	53	75	96	85	60	40	33	41	71	64	---	---	--	--
11	0.16	0.17	0.47	0.56	0.85	1.06	1.07	0.97	0.86	0.86	0.90	0.96	0.90	0.86	0.91	0.96	1.01
12	0.25	0.16	0.33	0.31	0.34	0.37	0.39	0.47	0.59	0.69	0.78	0.75	0.77	0.80	0.80	0.90	0.94
13	0.08	0.13	0.21	0.26	0.42	0.55	0.78	1.05	1.11	0.99	0.86	0.78	0.79	0.91	0.95	0.92	0.94
14	0.18	0.12	0.23	0.18	0.39	0.51	0.70	0.91	1.00	0.91	0.79	0.70	0.73	0.86	0.92	0.92	0.40

The absorption coefficient is expressed in percent for measurements 1 through 10 and in sabines for the measurements 11 through 14.

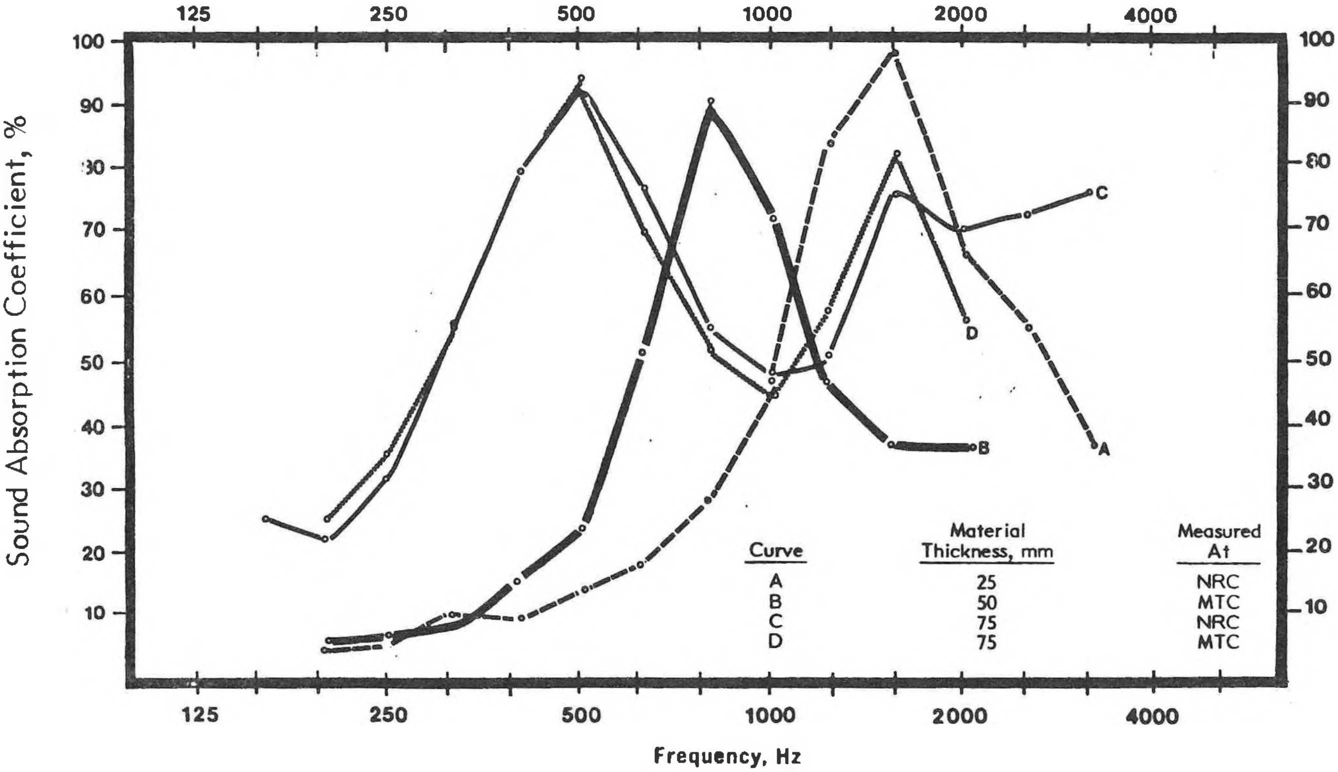

Fig. 1. Absorption coefficient of Durisol (absorbing layer, only) measured with standing wave tube.

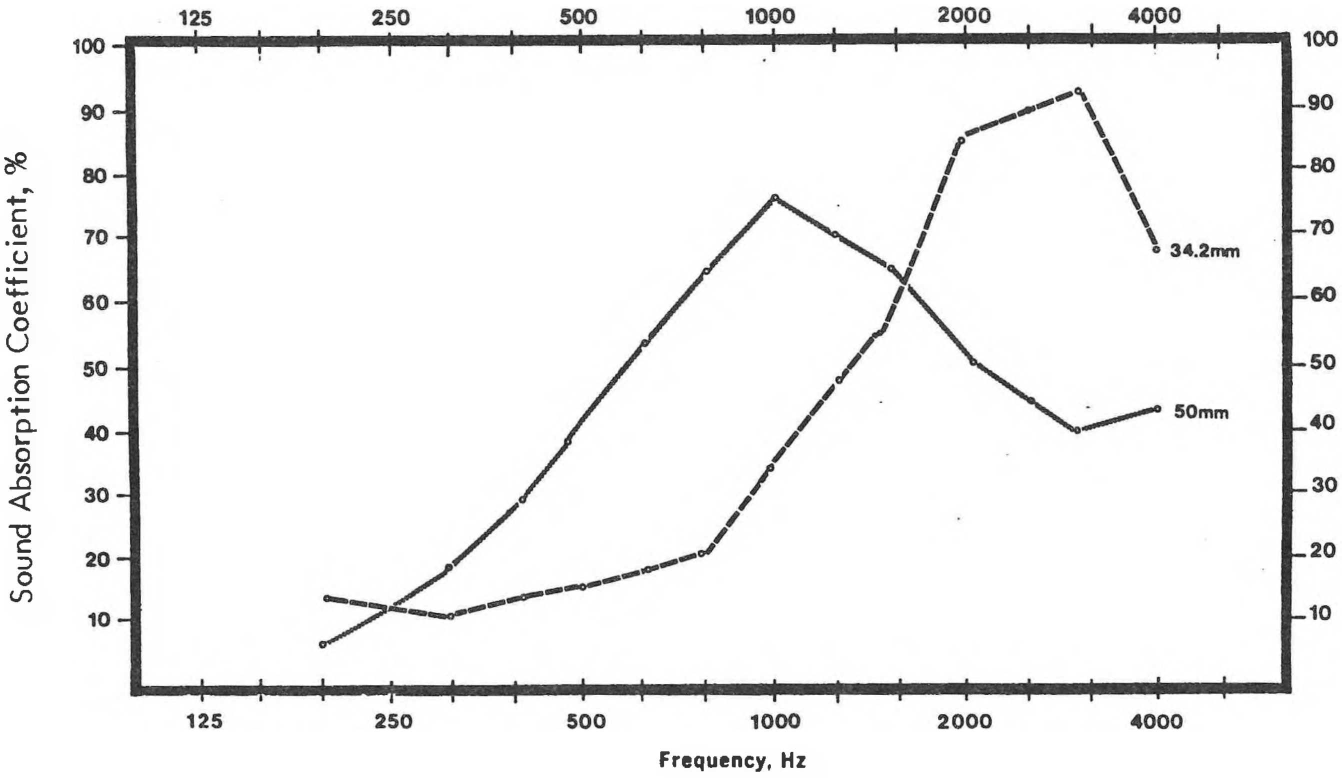

Fig. 2. Absorption coefficient of Herco Type 713 measured with standing wave tube.

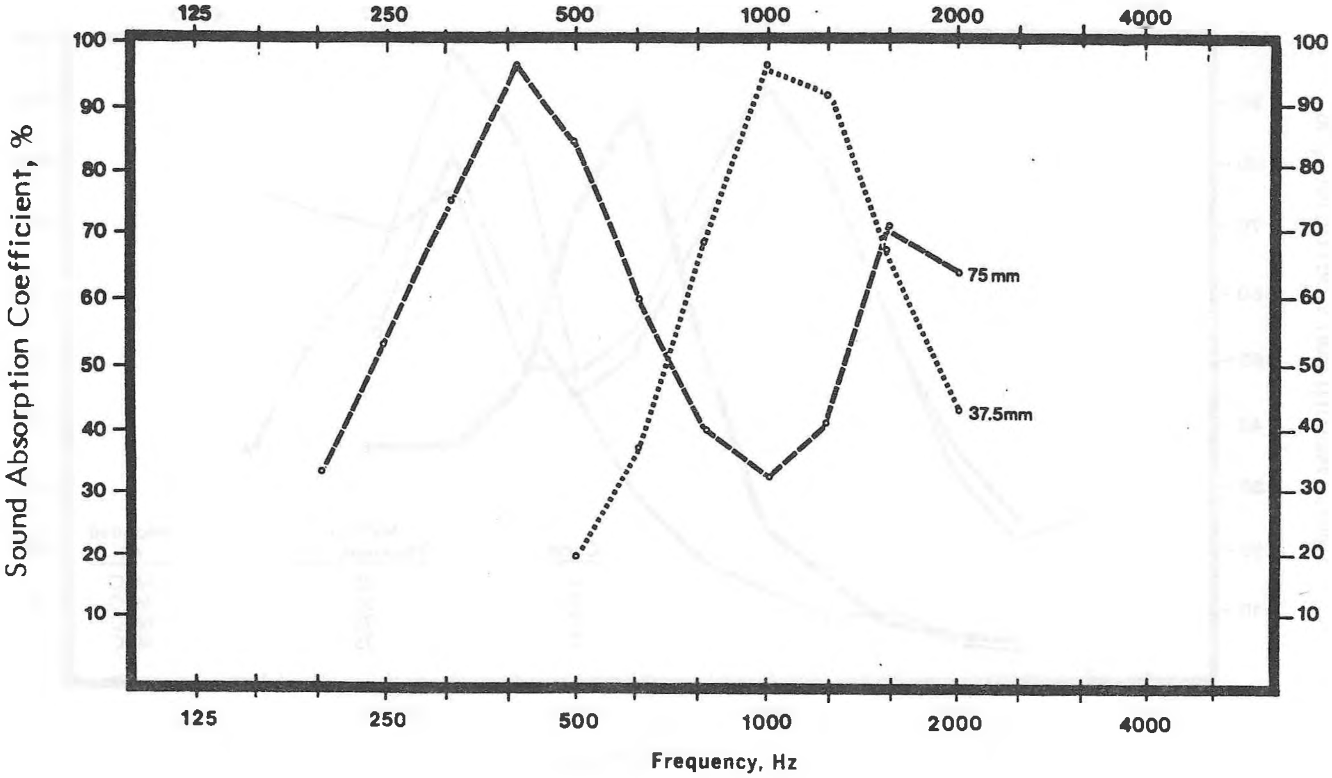

Fig. 3. Absorption coefficient of Petrical measured with standing wave tube.

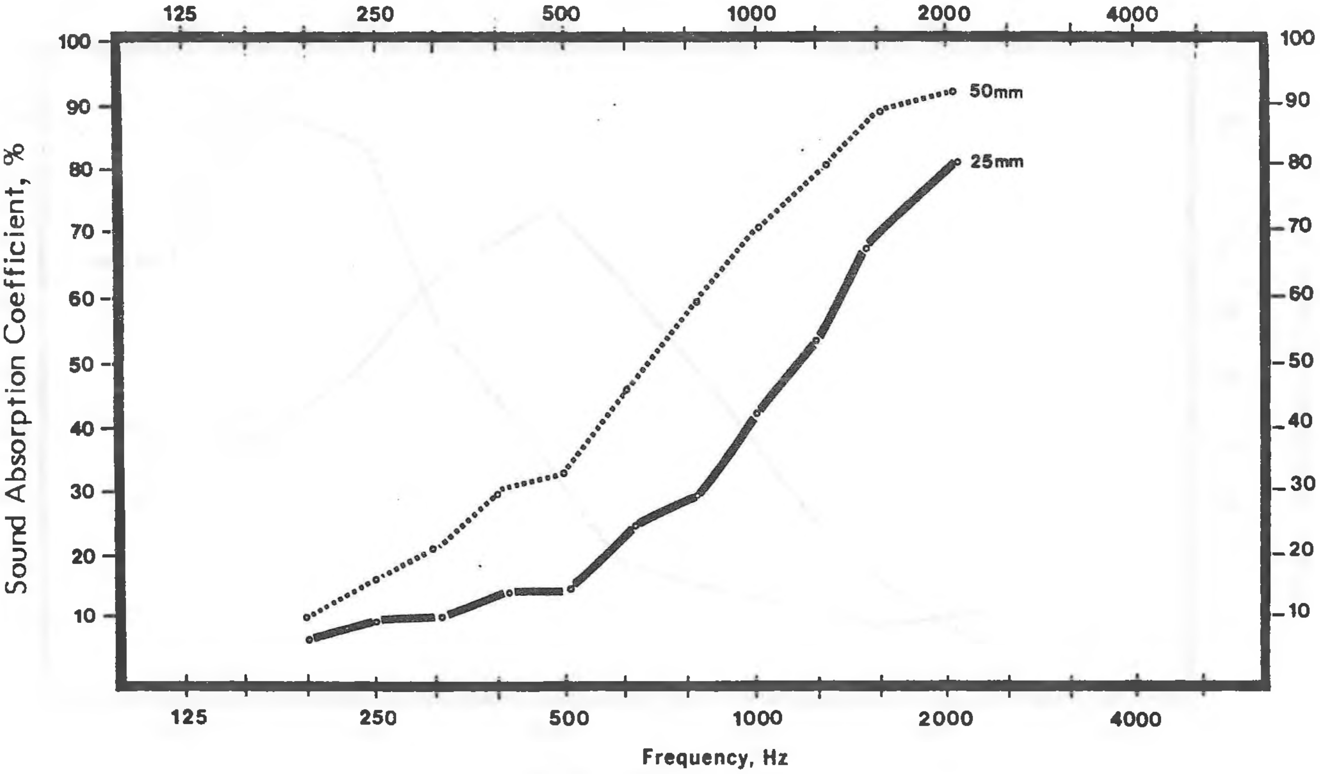

Fig. 4. Absorption coefficient of Fiberglas Type AF530, measured with standing wave tube.

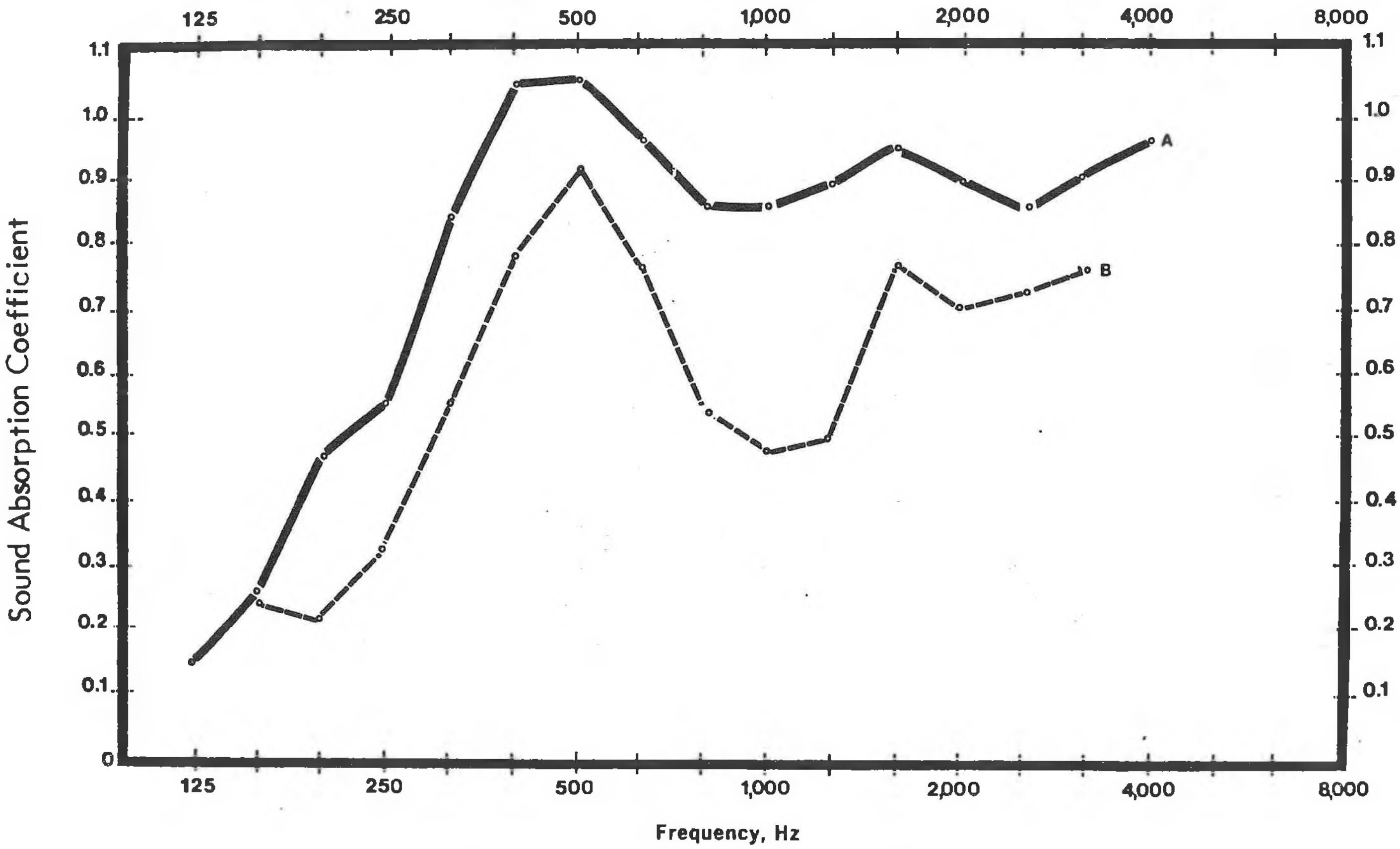

Fig. 5. Absorption coefficient of Durisol (absorbing layer, only): A - laid on floor in the reverberant room; B - in the standing wave tube.

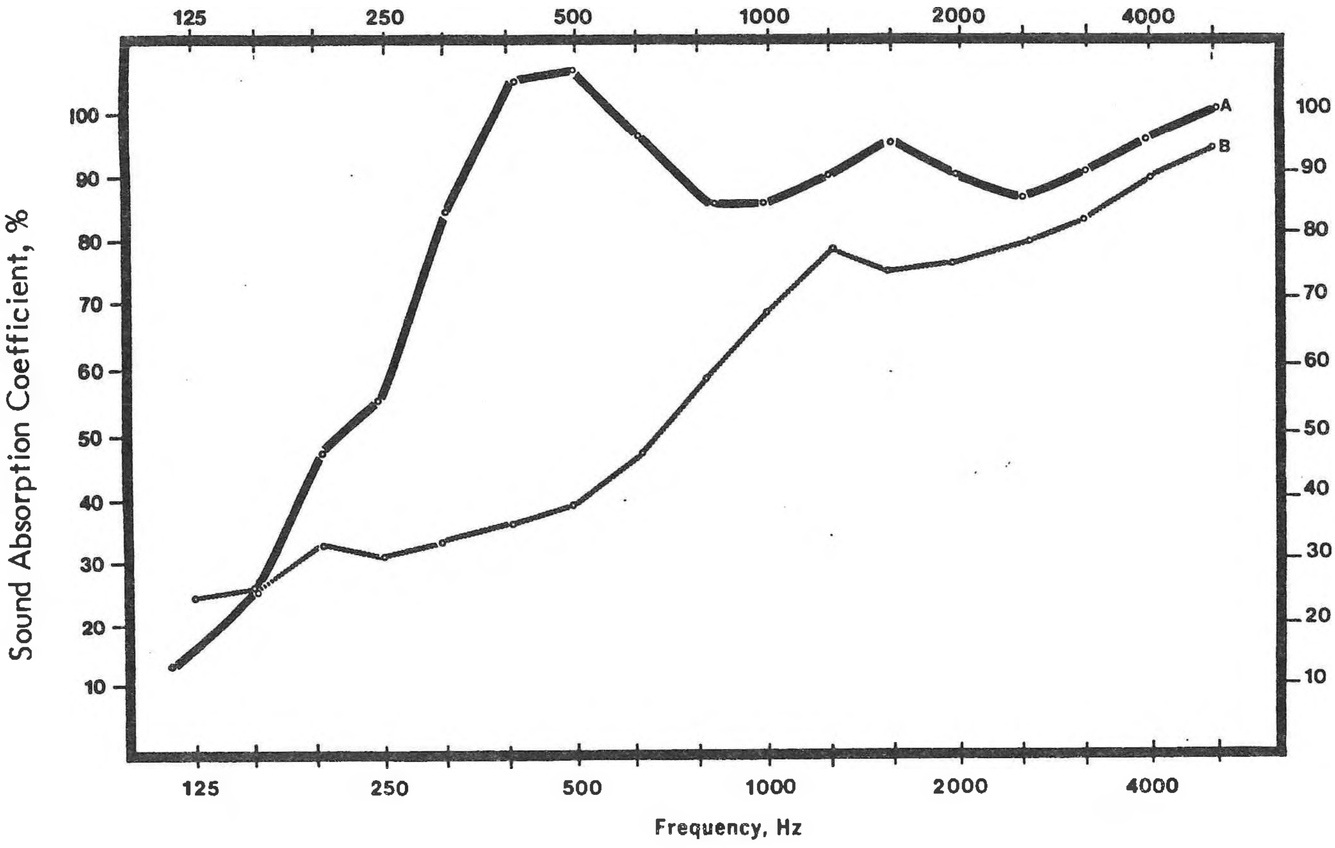

Fig. 6. Absorption coefficient of Durisol (absorbing layer, only) measured in the reverberant room: A - laid on floor; B - free standing position.

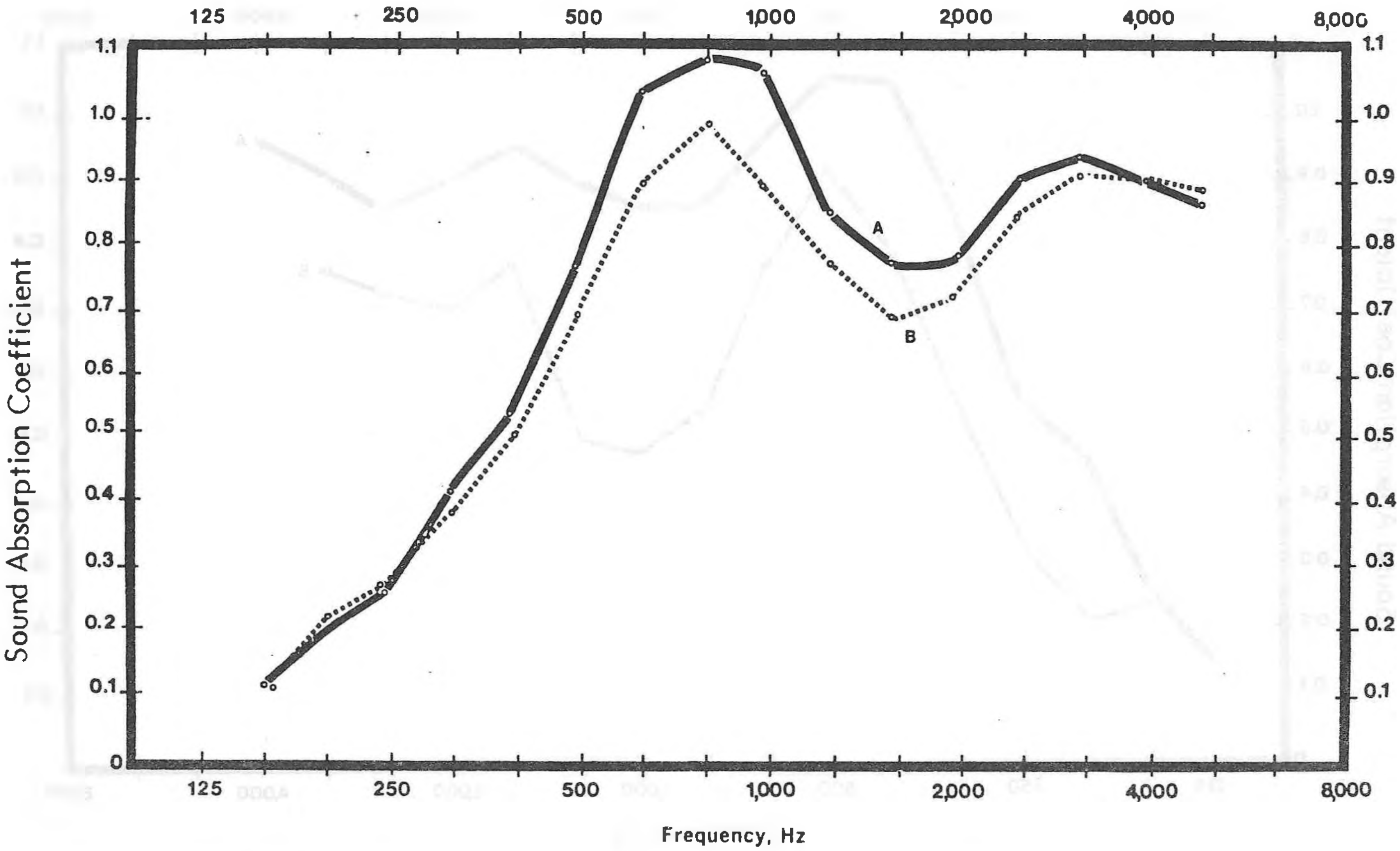

Fig. 7. Absorption coefficient of Durisol (complete panel) measured in the reverberant room: A - laid on floor; B - free standing position.

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Noise Testing of Vehicles—Acoustic Propagation Phenomena

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A RECURRING PROBLEM OVER THE LAST DECADE has been the variability of measurements using standard procedures for the noise testing of vehicles. What initially was believed to be a rather simple acoustic measurement has turned out in practice to include a surprising number of propagation phenomena, involving the state of the ground surface, the state of the atmosphere adjacent to this surface, and the interaction between the two. This paper represents an attempt to convey the author's current knowledge of these acoustic propagation phenomena to practicing engineers, hopefully in a form they will find useful.

Attenuation caused by the interference between direct and ground-reflected waves is considered first. This section is essentially an update of a review (1)* written six years ago, to which the reader is referred for a more detailed description of the basic phenomena. The next topic is atmospheric turbulence, where we consider the effect of atmospheric inhomogeneity along the propagation path of the noise on the variability of measurements. This inhomogeneity may be from naturally occurring atmospheric turbulence, or induced by the wake of the vehicle. Finally effects of refraction by the thermal boundary layer close to the ground are considered.

INTERFERENCE BETWEEN DIRECT AND GROUND-REFLECTED WAVES

Available theory relevant to ground interference effects (2) is developed in terms of the basic configuration shown in Fig. 1. A point source S and receiver R are situated above a plane earth. The direct sound travels along path r_1 to the receiver and the reflected sound along path r_2 which appears at the receiver to have come from the image source I. The interference between direct and reflected sound at R depends first of all on the reflective properties of the ground surface, which are usually expressed in terms of a complex acoustic impedance Z_2 of this surface relative to the characteristic impedance Z_1 of air. Both real and imaginary parts of Z_2 normally vary strongly with the frequency of the sound, and depend also on the grazing angle ψ.

The most detailed measurements of the impedance of a natural ground surface now available are for mown grass (3). A remarkably good fit to these measurements has been achieved by Chessell (4) using a simple model with a single adjustable parameter: the ground is assumed to reflect as if it were a semi-infinite porous medium, and the adjustable parameter is the flow resistivity σ - the resistance to flow of air in the pores per unit thickness of the ground (for which the only recognized unit is the rayl (CGS)).

To put present knowledge of ground interference into effective engineering practice a suitably simple technique is required, for measuring the ground impedance conveniently in any specific situation of interest. It would also be very useful to have measurements

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

A number of propagation phenomena which cause variability in the noise testing of vehicles using standard procedures have been isolated and studied. Included are the effects of interference produced by reflection from various ground surfaces, the effects of refraction caused by wind and temperature gradients in the atmosphere, changes in sound level due to the wake of the vehicle, and the effects of normal atmospheric turbulence.

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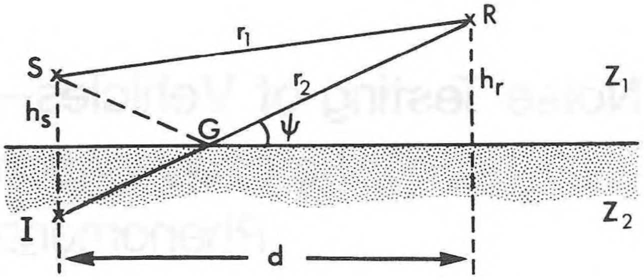

Fig. 1 - Reflection of sound from plane ground surface with impedance Z_2

obtained with this technique available for a variety of commonly encountered ground surfaces. With these goals in mind we have extended the analysis of Chessell to a variety of surfaces. It is accepted that the reflectivity of these surfaces may in time be better described by a more complex model, but the single parameter model is appropriate at present to both engineering needs and the present relatively primitive state of knowledge concerning the ground impedance.

POINT SOURCE - A single configuration was first chosen, that given by Fig. 1 with $h_s = 0.3m$ (1 ft), $h_r = 1.2m$ (4 ft), and $d = 15.2m$ (50 ft). This choice was to maximize the relevance for noise testing using existing standard procedures, for example the noise from a snowmobile (5) or the exhaust noise from an automobile or light truck (6). The family of curves shown in Fig. 2 was then calculated for this configuration using the same equations as Chessell. This figure gives the predicted sound level at the receiver in the presence of the ground as a function of frequency for a range of values of the flow resistivity σ. The sound level is relative to that for the same point source at the same distance in free space.

Measurements were also made in the field of the sound produced in this configuration by an acoustic point source (1) using a pure tone and swept frequency. By arranging through a separate feedback loop that the acoustic power output of the source was independent of frequency, the measured frequency spectrum could be compared directly with the family of curves shown in Fig. 2 to obtain a value of the effective flow resistivity σ. The real and imaginary parts of the ground impedance were then obtained over a range of frequency from this value of σ using published graphs (4). The whole procedure, starting with setting up the apparatus on the site and ending with values of σ on the ground impedance, takes about half an hour (7). Values of σ for a number of sites obtained in this fashion are shown in Table I. Note the wide range in σ, extending from about 10 rayls for newly fallen snow to 20,000 rayls or greater for

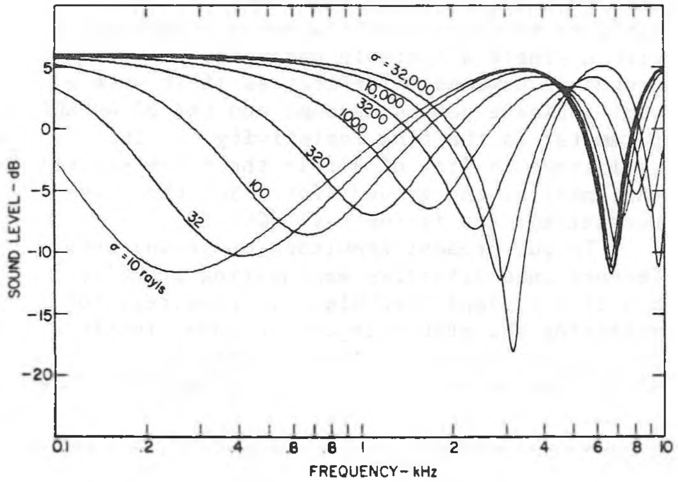

Fig. 2 - Predicted spectra for $h_s = 0.3m$, $h_r = 1.2m$ and $d = 15.2m$ in Fig. 1, and various values of the flow resistivity σ. The sound spectrum level is relative to that from the same point source at the same distance in free space

Table I - Flow Resistivity for Various Ground Surfaces

Description of Surface	Flow Resistivity Giving Best Fit To Measured Spectrum: CGS Rayls
Dry snow, new fallen 7.5cm on a 40cm base	10 to 30
Sugar snow	25 to 50
In forest, pine or hemlock	20 to 80
Grass: rough pasture, airport, public buildings, etc.	150 to 300
Roadside dirt, ill-defined, small rocks up to 4"	300 to 800
Sandy silt, hard packed by vehicles	800 to 2500
"Clean" limestone chips, thick layer (1/2 to 1 inch mesh)	1500 to 4000
Old dirt roadway, fine stones (1/4" mesh) interstices filled	2000 to 4000
Earth, exposed and rain-packed	4000 to 8000
Quarry dust, fine, very hard-packed by vehicles	5000 to 20,000
Asphalt, sealed by dust and use	>20,000

old asphalt or concrete, and the variation in the excess attenuation shown in Fig. 2 that this range signifies.

APPLICATIONS - The relevance of the curves in Fig. 2 for vehicle testing may be understood by considering the spectrum of snowmobile noise in Fig. 3 measured using standard test procedures (5) over grass. It is well known that the maximum overall A-weighted level using these procedures is strongly site-dependent, and comparison of the spectrum in Fig. 3 with the inverse A-weighting curve shows the peaks due to the harmonics of the engine firing frequency to be significantly reduced in the region of 0.5 to 1 kHz due to the excess ground attenuation. Comparison of ground attenuation curves in Fig. 3 for σ = 150-300 rayls relevant for grass with those for 10-50 rayls relevant for snow indicates the differences one should expect for testing over these different surfaces.

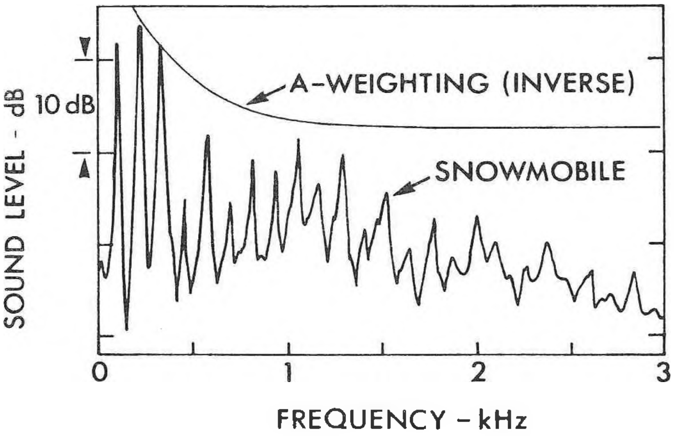

Fig. 3 - Measured snowmobile spectrum

One may note also that a test surface normally allowed for construction machinery is packed dirt. The ground attenuation indicated in Fig. 2 for σ in the range 800-2500 rayls found for hard-packed sandy silt (Table I) is by no means the same as that for a hard surface such as asphalt or concrete ($\sigma \geq 30,000$).

It should be noted also, that it is not necessary to use the particular configuration $h_s = 0.3m$, $h_r = 1.2m$, and $d = 15.2m$ either to determine σ via the procedure described above or to predict the excess attenuation due to the ground effect. A set of curves similar to those in Fig. 2 can be calculated using the same equations for any configuration.

LINE SOURCE - The positions of the sharp dips in the spectrum shown in Fig. 2 for hard surfaces ($\sigma \geq 30,000$ rayls) at 3 kHz and 9 kHz are strongly dependent on the measurement configuration, as they occur where the difference in path length between direct and reflected rays ($|r_2-r_1|$ in Fig. 1) are ∿1 and 3 half-wavelengths of sound respectively. For elevated noise sources such as truck exhaust stacks these dips occur down in the sensitive 0.1 to 1.0 kHz range of frequency where they provide a variability problem (1), while at larger distances they move up in frequency. It has been argued from time to time that the ground interference problem would be eased if an integrating sound-level meter were used for vehicle pass-by tests, as the interference filter shown in Fig. 2 should be greatly smoothed by the varying distance.

To test this hypothesis the sound level from an incoherent line source normal to the paper at point S in Fig. 1 has been calculated for otherwise the same configuration as that for Fig. 2 ($h_s = 0.3m$, $h_r = 1.2m$ and $d = 15.2m$ in Fig. 1). The results of these calculations are shown in Fig. 4. The reference level is again that for the same line source at the same distance in free space.

Comparing the curve in Fig. 4 for 20,000 rayls with that in Fig. 2, we find that the first dip in Fig. 4 is certainly much shallower than that in Fig. 2, but it has by no means disappeared by this smoothing process, and would probably still present a problem. The minima at lower frequencies for σ = 30 and 300 rayls are little changed in Fig. 4 from those for a point source in Fig. 2 because here the cancellation is due mainly to the change in phase on reflection rather than a difference in path length.

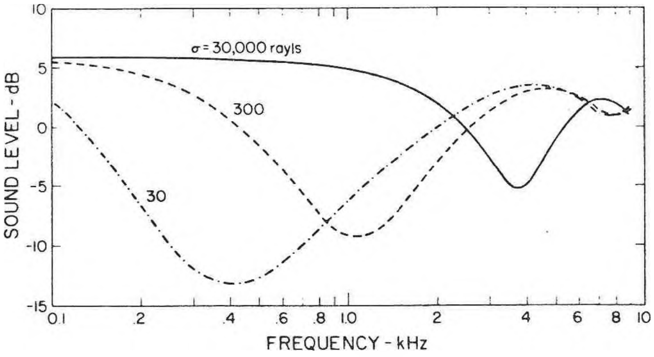

Fig. 4 - Predicted spectra for an incoherent line source and various values of the flow resistivity σ. The spectrum level is relative to that from the same source at the same distance in free space

It should be noted that the one parameter model used here, together with a relevant table of values for flow resistivity similar to Table I, if inserted into prediction schemes for environmental noise would represent a considerable advance over present procedures.

ATMOSPHERIC TURBULENCE

Large eddies are formed in the atmosphere by instabilities in the thermal and viscous boundary layers at the surface of the ground.

Further instability causes these eddies to break down progressively into smaller and smaller sizes until the energy is finally dissipated by viscosity in eddies approximately 1mm in size. A statistical distribution of eddies, which we call turbulence, is therefore present in the atmosphere at all times. The intensity of the turbulence is dependent on meteorological conditions, being high, for example, on a windy summer afternoon, and low under nocturnal inversions.

The inhomogeneity of the atmosphere in normal conditions of turbulence is much larger than is generally appreciated. Shown in Fig. 5 are typical daytime records of wind velocity and temperature. These measurements were taken simultaneously 1m above a large flat vehicle test area. Note for example that fluctuations in temperature of 5°C which last several seconds are common in the "steady" wind ($t<120$ sec in Fig. 5) and 10°C not uncommon. When the wind decreases to very low or zero velocity, slow drifts in temperature of the same magnitude are present, as for instance for $t \approx 180$ sec in Fig. 5.

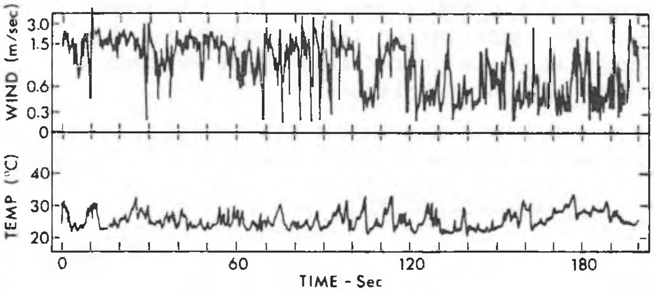

Fig. 5 - Typical daytime records of wind velocity and temperature. The measurements were taken simultaneously at a height of 1m over a large flat test area

The effect of normal atmospheric turbulence on wave propagation from a point source under conditions relevant to vehicle testing are now reasonably well established (8). Fluctuations of sound level (in decibels) of a pure tone should increase approximately as the square root of the frequency and linearly with distance.

AN EXPERIMENTAL INVESTIGATION - A series of experiments were conducted to find the influence of atmospheric turbulence in the propagation path, as well as other factors, on the variability of vehicle noise tests (9). The noise from an accelerating automobile was first measured (and tape-recorded) as specified by standard SAE J986a five times in succession (test 1). A multitone point source was then placed 0.3m above the ground at the point in the vehicle path closest to the microphone position. Without moving the microphone (or the source) 3 minutes of constant sound output from the multitone source was then tape-recorded. (The measurement configuration was here that shown in Fig. 1 with $h_s = 0.3$m, $h_r = 1.2$m and $d = 15.2$m.)

For the third test the multitone point source was attached to the automobile beside the exhaust outlet (which was the same height, 0.3m above the ground). The vehicle was run by the microphone in the same SAE J986a configuration used in the first test but at a constant speed of 48 kph (30 MPH). When near the microphone the engine was switched off and the multitone source switched on. Records of the sound from a calibrated point source simulating the exhaust noise from a moving vehicle were thereby obtained. This test was also repeated 5 times.

The sequence of three tests was conducted for one vehicle in about thirty minutes, and they were repeated for three vehicles. The whole sequence for three vehicles was also repeated for three different test sites and on twelve days selected for different weather conditions.

Run-to-run Variability - The characteristics of run-to-run variation were first investigated by frequency analysis (followed by statistical analysis) of the tape recordings for a given site and day. The standard deviation of the sound spectrum levels for two different days are shown in Fig. 6. The S's on the right give the variability of the amplitude of the pure tones received at the microphone from the stationary point source (test 2). Their characteristics are what is expected for propagation in normal atmospheric turbulence, as described above: the fluctuations in amplitude increase with increasing frequency and are larger for the day, when the sun is heating the ground, than for the evening.

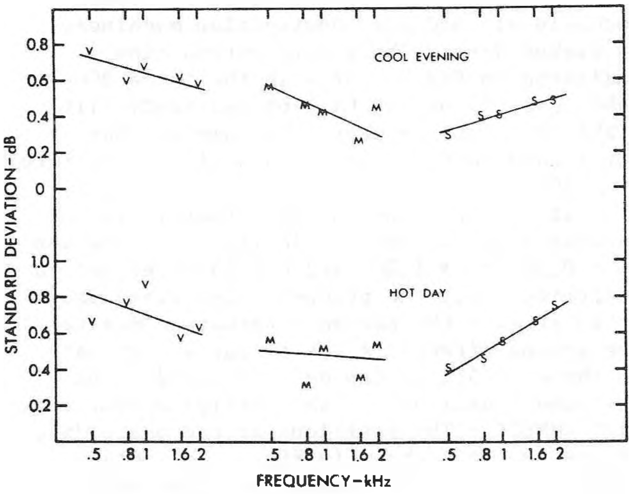

Fig. 6 - Standard deviations of sound level fluctuations for moving vehicles V, moving multitone source M and stationary multitone source S on a hot day and a cool evening - run-to-run variability

The M's in the center of Fig. 6 give the run-to-run variability in the maximum level of the pure tones from the moving point source (test 3) and the V's on the left the run-to-run variability in the maximum level of corresponding 1/3 octave bands of noise achieved by the accelerating vehicle (test 1). Comparing the characteristics of the M's, V's and S's, we find the behaviour of the M's and V's to be similar to each other, and different from that of the S's. The variability for both the accelerating vehicle and moving point source decrease (or at least don't increase) with increasing frequency, and also the difference between hot day and cool evening is not significant.

The similarity of M's and V's indicates that the performance of the vehicle or operator was not a factor in the V's, because the M's are for a calibrated source. The difference in behaviour between M's and S's indicates that both V's and M's are the result of motion of the vehicle (as the M's and S's are from the same point source). The likely mechanism, which fits the characteristics of the M's and V's in Fig. 6 is atmospheric turbulence caused directly by the wake of the vehicle. The greater variation at low frequencies is consistent with more large eddies than would be present in the stable statistical distribution of sizes described above. This is reasonable because the wake is the primary eddy, which exists before the stable distribution has time to form.

Day-to-day Variability (Effect of Weather) - The day-to-day variation of the A-weighted sound level was examined for a given site and type of test, and compared with the day-to-day variation in meteorological variables, namely temperature, temperature gradient, wind velocity and wind direction. The only significant correlation found was with the temperature.

The deviation of the sound level measured for accelerating vehicles using SAE J986a test procedures (test 1), when averaged for each site and day, from the mean for all days is shown in Fig. 7 plotted against the ambient temperature measured 1m above the ground. The dashed lines are fitted to the points for each site A, B or C individually, and the solid line gives the fit to all sites. The correlation with temperature, and the dependence on temperature given by the lines are comparable to what has been found elsewhere, and represent a considerable deterrent to regulation. The usual explanation of this temperature dependence is in terms of the density of the charge flowing through the engine and exhaust system.

However, we also examined the correlation of the day-to-day deviations for accelerating vehicles (test 1) shown in Fig. 7 with the equivalent for the moving point source (test 3) and those for the stationary source (test 2). The correlation of the test 3 results with those of test 1 was fairly high (62%), while the correlation of the test 3 results with those of test 2 was low (24%) (10).

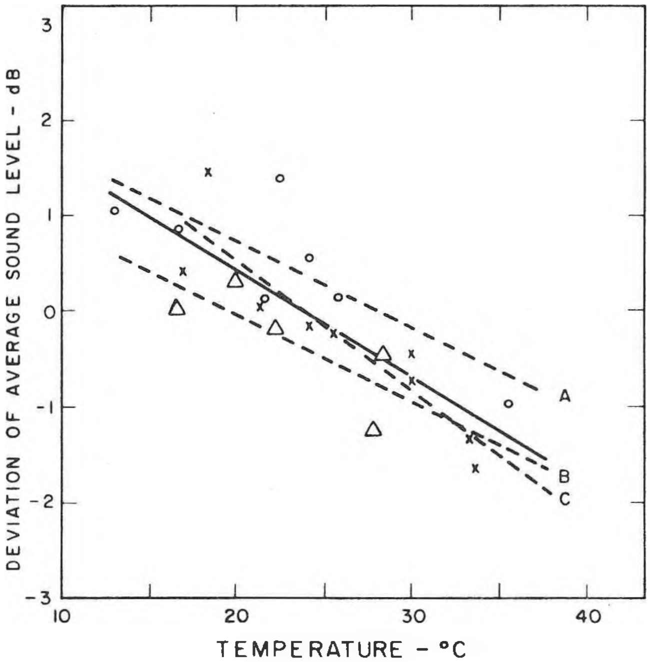

Fig. 7 - Deviations of average sound level attained for accelerating vehicles on different days from the mean for all days: O site A, Δ site B and X site C. The dashed lines are fitted to the points for each site, and the solid line to all points (day-to-day variability)

These measured correlations are incompatible with the day-to-day variation in measured sound levels for accelerating vehicles, as in Fig. 7, being in the noise source, as in the usual explanation given above. A substantial portion of it must lie in the motion of the vehicle, independent of the source, to provide the 62% correlation with the tests using an independent calibrated point source which moves with the vehicle, and the low correlation with the same source when stationary. Presumably this contribution is from the vehicle wake, as is the case with the run-to-run variability described previously.

REFRACTION

For acoustic propagation outdoors over distances longer than about 30m the effect of curved ray paths, or refraction, usually needs to be considered. The principal effects are illustrated in Fig. 8. For propagation downwind, or under temperature inversions (common at night) the refraction is downward, as shown at "a". The main effect here is usually to reduce the attenuation caused by ground interference. For propagation upwind, or under temperature lapse conditions, the sound refracts upwards as shown at "b" in Fig. 8. The main

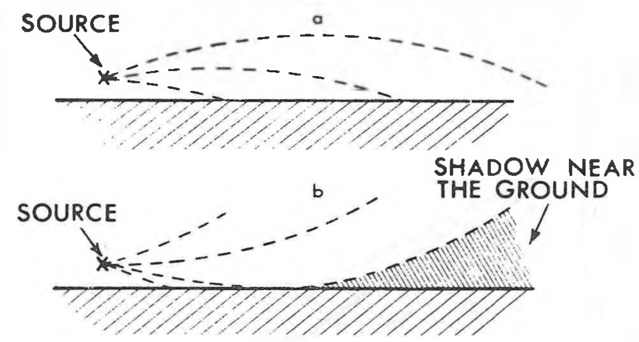

Fig. 8 - Forms of refraction, (a) for propagation downwind or during an inversion, and (b) for propagation upwind or during temperature lapse conditions

effect here is the creation of shadow zones, as indicated in the figure, where the sound level is commonly reduced by as much as 20 dB. In both cases, there exists a gradient of sound velocity in the atmosphere, and the refraction is towards the low velocity region.

For the noise testing of vehicles, significant propagation distances are normally kept to 15m or less in order to avoid these refraction effects, which would otherwise provide a strong dependence of measured sound level on the weather. However one needs a clear understanding of refraction phenomena to know when a measurement is at risk in unusual conditions.

THERMAL BOUNDARY LAYER - For significant refraction effects to occur in short distances, strong gradients of sound velocity are needed in the atmosphere, and one such gradient always exists close to the ground during sunny weather, caused by the heating of the ground surface by the sun.

Measurements of the vertical profile of temperature close to a paved test site on a sunny summer afternoon (9) where there is a relatively constant wind velocity of ~6m/sec, and also on a calm cool evening for comparison, are shown in Fig. 9. The error bars give a rough indication of the variation in temperature. Note the existence of a thermal boundary layer during the daytime, which is confined in thickness to about 30cm by the wind, and that this layer virtually disappears in the evening. The narrow peaks on the temperature record for a height of 1m in Fig. 5, for example, are rising bubbles of hot air carried away by the wind, known as thermal plumes to the meteorologist.

The thickness of the boundary layer tends to increase with decreasing wind velocity, as the wind then becomes less effective at carrying away the hot air. The general increase in temperature shown in Fig. 5 for t≈180 sec indicates that the thickness of the boundary layer becomes larger than 1m during calm spells.

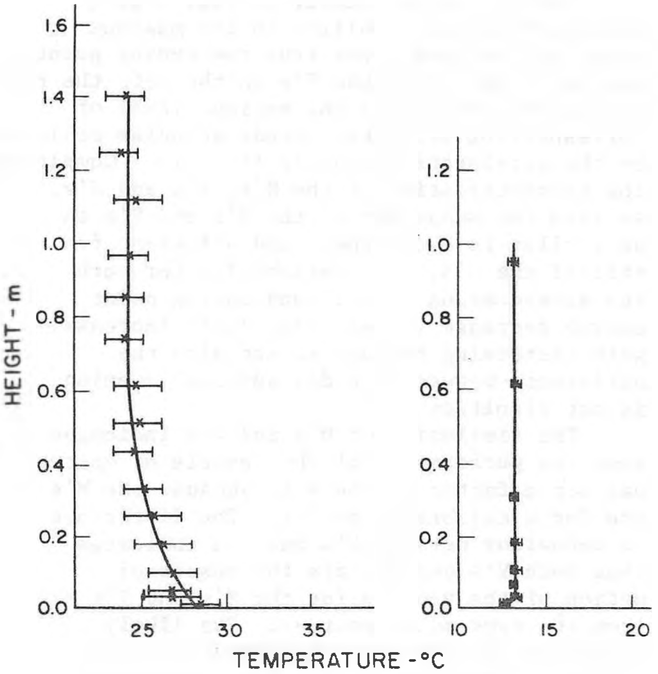

Fig. 9 - Measured vertical profiles of temperature over a large flat test site during a sunny and windy day on the left, and on a cool evening to the right

ACOUSTIC MIRAGE - It is a common experience when driving an automobile to see what is apparently a pool of water on the road ahead, but in reality is a portion of the sky ahead, the light ray from which has been refracted upwards to the eye by the thermal boundary layer. This phenomenon is usually called a mirage. Since the velocity of sound is 1700 times more sensitive proportionally to the temperature than the velocity of light, powerful acoustic mirages (and shadow zones) must appear somewhere, due to the thin thermal boundary layer shown in Fig. 9, although this phenomenon does not seem to have been reported previously in the scientific literature.

To find whether such a mirage could influence measurements of vehicle noise, an acoustic point source emitting a pure tone was placed right on the surface on a flat asphalt site. Vertical profiles of both temperature and sound level were then measured on the site. The temperature profiles were similar to the daytime one shown in Fig. 9. The dashed lines in Fig. 10 show the measurements of sound level at a distance of 15m from the source and a height of 1.0m, for propagation both upwind and downwind, and the solid lines the same for a height of 0.5m. The sound level is relative to that for the same distance in free space.

Note that there is no significant excess attenuation of sound due to the thermal boundary layer at a height of 1.0m, but at 0.5m the excess attenuation becomes large, 10 dB or

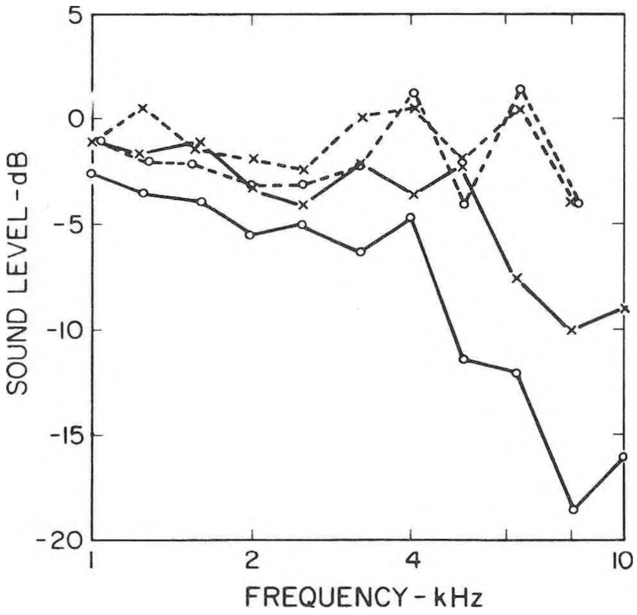

Fig. 10 - The acoustic mirage effect for propagation upwind (O) and downwind (X) for a microphone height of 1.0m --- and 0.5m ——. The spectrum level is relative to that from the same point source at the same distance in free space

greater, for frequencies greater than 4 kHz. There is at this distance from the source, therefore, a shadow boundary of the type shown in Fig. 8 at a height between 0.5m and 1.0m for frequencies higher than 4 kHz. The wind, whose velocity measured at a height of 1.3m averaged 1.0 to 1.2m/sec, was insufficient to destroy this shadow, although it did significantly affect the attenuation in the shadow zone (see Fig. 10). The shadow zone is present only at high frequencies, because the thickness of the boundary layer becomes small relative to the wavelength at low frequencies, hence ineffective as a wave refractor.

Measurements at a distance of 7.5m (not shown) indicated the shadow zone to be still present, but the shadow boundary to be lower than 0.5m. The measurements at ground level for this distance closely resembled those shown in Fig. 10 for a height of 0.5m.

Shadow zones may thus be present in acoustic measurements outdoors, at distances of 7.5 and 15m relevant to vehicle testing, in the presence of a thermal boundary layer similar to that shown in Fig. 9, due to this mirage effect. The significance of this shadowing for compliance testing of vehicles using procedures such as SAE J986a seems marginal. However the atmospheric conditions for the measurements shown in Fig. 10 should not be taken as an extreme. The dimensions of the boundary layer are obviously very volatile, and the shadow zones may be much enhanced for a hotter pavement or lower wind velocity, as an example. Thus care should be exercised in neglecting this effect for unusual conditions, particularly if a low microphone position is adopted.

The mirage effect shown in Fig. 10, however, throws considerable doubt on existing measurements of tire noise, where the noise source is presumably very close to the ground. The high frequency roll-off in spectrum level, characteristic of published measurements of tire noise, could be caused by refraction in the thermal boundary layer on the measurement site, rather than being characteristic of the tire. In practical situations where tire noise is important, for example in the propagation of noise from highways, this effect should also be taken into consideration.

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