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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'Acoustique c/o JASCO Applied Sciences 2305–4464 Markham Street Victoria, BC V8Z 7X8 - - - secretary@caa-aca.ca - Dr. Roberto Racca

Contents - Table des matières

Editor's note: from the Year of Sound to a 165 Hz world
Éditorial : De l'année du son à un monde à 165 Hz

From the Year of Sound to a 165 Hz world

Dear reader, you may remember from our last issue in December where Michael Taroudakis, President of the International Commission for Acoustics, announced the preparations for the celebration of an International Year of Sound for the 2020 (IYS 2020). Worldwide, we were ready to start the planning of the events organized by each ICA National Society (and so by CAA too!) as well as we were collaborating for some international events too.

We opened the celebration in Paris last January 31, before we all realized this would have been a different year. Since then, COVID-19 has become our main concern, and we are all trying to stay safe, possibly at home (whenever possible). Cities are becoming quieter. We have more opportunities to rediscover natural sounds and we are starting reflecting on the world after COVID-19 too. Will we leave in a quieter environment? Will we slow down? Will COVID-19 be a transition point for the humankind?

What we have learned for now is that we need to practice social distance. In the coming weeks, we need to resonate at 165 Hz, the frequency of a sound that (in the air) has a wavelength of 2 meters. We all need to try to leave 2 meters apart from each other for now.

Well, in this context, I present to you the first issue of 2020. It is an issue that hopefully maybe a pleasant read and support your days. An issue will help us to fly with the mind.

The issue confirms the increasing attention our journal receives among authors worldwide, and we will have the opportunity to read about temples in China, a church in Italy but also research on ultrasound imaging and other biomedical applications. Finally, at the end of the issue, you will find the membership directory of our association.

I wish you a pleasant reading of this issue.
Umberto Berardi
Editor in Chief.

De l'année du son à un monde à 165 Hz

Chère lectrice, cher lecteur, vous vous souvenez peut-être de notre dernier numéro de décembre où Michael Taroudakis, président de la Commission internationale d'acoustique, annonçait des préparatifs pour la célébration d'une année internationale du son en 2020. Dans le monde entier, nous étions prêts à lancer la planification de ces événements, chacun organisé par les différentes sociétés nationales de l'ICA (dont la CAA !), car nous devions collaborer à certains événements internationaux.

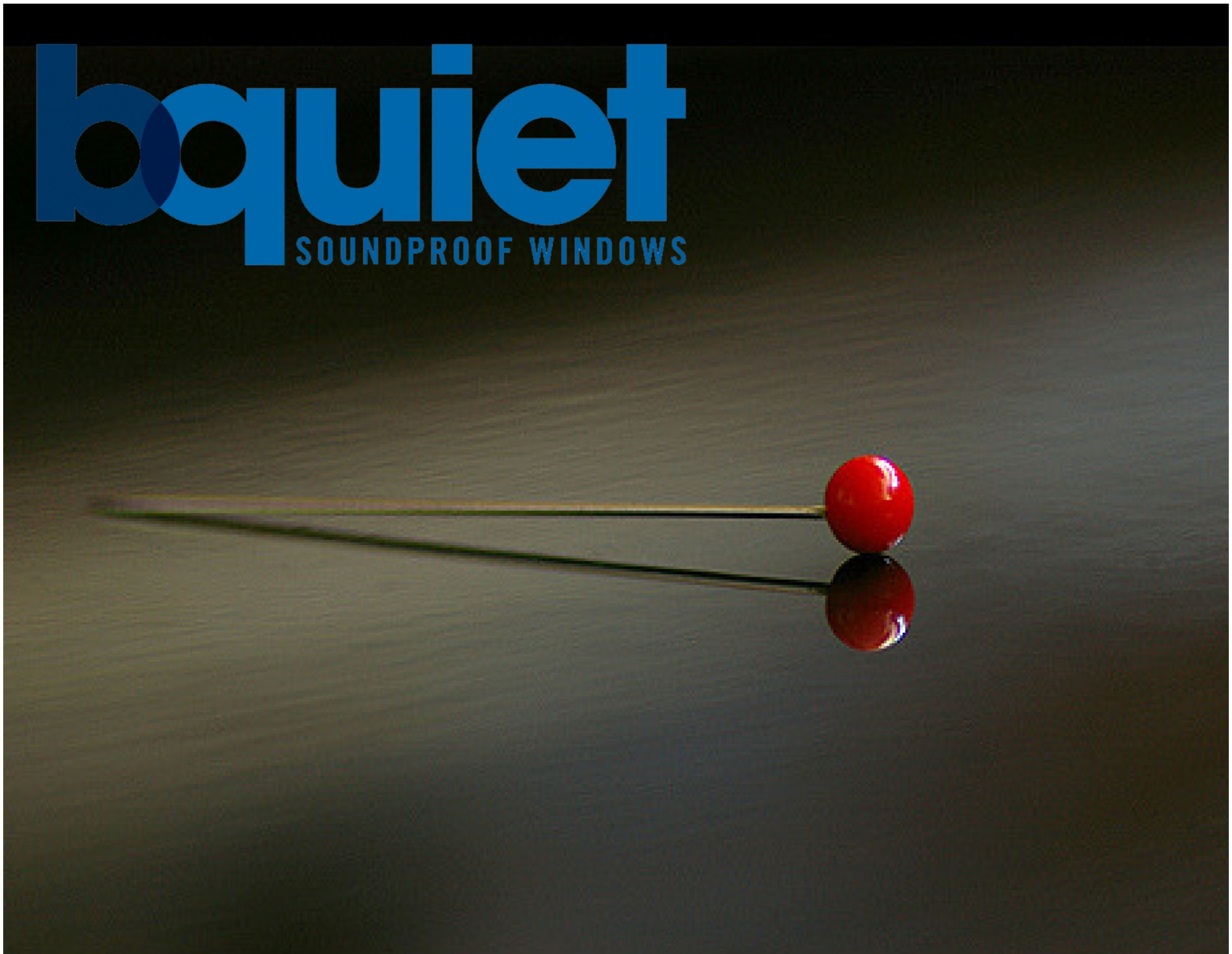
Cette célébration s'est ouverte à Paris, le 31 janvier dernier, avant de réaliser que cette année serait bien singulière. Depuis, la COVID-19 est devenue notre principale préoccupation et nous essayons tous de rester en sécurité : dans la mesure du possible à la maison. Les villes redeviennent silencieuses. Alors que nous avons l'occasion de redécouvrir les sons de la nature, nous commençons à imaginer un monde après la COVID-19. Sera-t-il plus silencieux ? Plus calme ? Plus lent ? La COVID-19 sera-t-elle un point de transition pour l'humanité ?

Aujourd'hui, nous apprenons à pratiquer la distance sociale. Dans les semaines à venir, nous devons résonner à 165 Hz, la fréquence d'un son qui (dans l'air) a une longueur d'onde de 2 mètres. Nous devons tous essayer, pour l'instant, de nous éloigner de 2 mètres les uns des autres.

C'est dans ce contexte que je vous présente le premier numéro de 2020. C'est un numéro qui, nous l'espérons, sera une lecture agréable pour remplir vos journées. Un numéro qui nous aidera à nous évader par l'esprit.

Ce numéro nous confirme l'attention croissante d'auteurs du monde entier envers notre revue. Ainsi, nous aurons l'occasion de lire aussi bien sur les temples en Chine, sur une église en Italie, sur de la recherche en imagerie ultrasonore, que sur des applications biomédicales. Enfin, vous trouverez le répertoire des membres de notre association à la fin de ce numéro.

En vous souhaitant une agréable lecture.
Umberto Berardi
Rédacteur en chef


bquiet
SOUNDPROOF WINDOWS

From Butterfly to Propeller

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Résumé

Le potentiel de la "peau acoustique du papillon", en tant que nouvelle méthode de réduction du bruit aéroacoustique pour une hélice silencieuse, a été évalué. Ce sujet est particulièrement pertinent en raison de l'augmentation des hélices à usage civil comme militaire avec de multiples problèmes opérationnels. La réduction du bruit comme l'efficacité d'un système propulsif sont des aspects clés dans la conception des véhicules aériens avancés et peuvent très souvent conduire au succès ou à l'échec d'une mission. L'attention a été portée sur ce problème par l'observation des écailles poreuses de lépidoptères et de leurs propriétés de réduction du bruit : la couverture des mites permet à ces insectes de surmonter les attaques des chauves-souris la nuit. Ces appendices sont très petits (taille : 30 - 200 µm) et ont une structure poreuse différente. Bien que de nombreuses structures d'écailles poreuses de lépidoptères aient été discutées, seules les écailles poreuses des papillons *Papilio nireus* et *Delias nigrina* sont abordées ici. Deux conceptions de "peau acoustique de papillon" imitent les écailles creuses des ailes du papillon *Papilio nireus* (région creuse) et du papillon *Delieas nigrina* (région poreuse). Les résultats illustrent l'influence de structure de type "peau acoustique du papillon" sur les performances acoustiques d'une hélice à deux pales. Pour un nombre de Reynolds de 200000, la réduction du bruit d'une hélice en rotation type "peau acoustique de papillon" à région poreuse est de 4 dB, quand une hélice de type "peau acoustique de papillon" à région creuse est de 2 dB. La modification des effets acoustiques sur l'hélice en rotation avec la "peau acoustique de papillon" est due à la fois à une absorption acoustique, à une dissipation de l'énergie turbulente, à une réduction de l'influence sur le bruit généré et à une réduction de la différence de pression. D'autres études sur la "peau de papillon" ont montré que cette structure augmentait la force de portance et réduisait les vibrations de l'aile. Une étude expérimentale de l'effet du BAS sur les vibrations et les performances aérodynamiques de l'hélice n'entrait pas dans le cadre de cette expérience. Une explication complète, avec différentes vitesses de vent et de rotation des pales, est attendue pour des études plus détaillées. Mais il ne semble pas déraisonnable de suggérer la possibilité d'une géométrie optimale du BAS et de sa structure pour augmenter encore la poussée et réduire le bruit et les vibrations de l'hélice.

Mots clefs : *lepidopterans*, bruit, écailles poreuse, hélices, peau.

Abstract

The potential of the 'butterfly acoustical skin', as a new method of reduction aero acoustical noise for a quiet propeller, has been evaluated. This topic is particularly relevant due to the increase of the propellers for civil and military purposes with multiple operational issues. The quietness and efficiency of the propulsive system are key aspects in the design of advanced aerial vehicles and very often can lead to the success or failure of a mission. Attention was directed to this problem by the observation of the porous scales of *lepidopterans* and of there noise reduction properties: the moth coverage allows these insects to overcome bat's attacks at night. These appendages are very small (size: 30 – 200 µm) and have a various porous structure. Althought many structures of the porous scales of *lepidonterans* were discussed, here only the porous scales of the butterflies *Papilio nireus* and *Delias nigrina* are discussed. Two designs of "acoustic butterfly skin" imitate the hollow scales on the wings of the *Papilio nireus* butterfly (hollow region) and the *Delieas nigrina* butterfly (porous region). The results illustrate the influence of "acoustic butterfly skin" type structure on the acoustic performance of a two-bladed propeller. For a Reynolds number of 200,000, the noise reduction of a rotating propeller of the "acoustic butterfly skin" type with a porous region is 4 dB, when a propeller of the "acoustic butterfly skin" type with a hollow region is 2 dB. The modification of acoustical effects on the rotating propeller with 'butterfly acoustical skin' was due both to an acoustic absorption, to a dissipation of turbulent energy, to a reducing influence on noise generated and to reducing the pressure difference. It was determined in qualitative researches that the 'butterfly acoustical skin' influenced on the acoustic perfor-mances of two-bladed propeller. Other studies of 'butterfly skin' shoved that the skin increased the lift force and reduced the wing vibration. An experimental investigation of the effect of BAS on vibration and aerodynamic performances of propeller was not within the scope of this experiment. A full explanation, with different wind speeds and blade RPM, must await more detailed studies. But it does not seem unreasonable to suggest the possibility of some optimal BAS geometry and its structure to further augment thrust and reduce the noise and vibration of propeller.

Keywords: *lepidopterans*, noise, porous scales, propeller, skin.

1 Introduction

1.1 Propeller

A propeller is a type of aeronautical propulsion system that transmits power by converting rotational motion into thrust. A history of aerodynamic propeller usually begins with mention of the Chinese flying top (ca. 400 B.C.) which was a stick with a propeller on top, which was spun by hands and released [1]. Among da Vinci's works (late 15th century) there were sketches of a machine for vertical flight using a screw-type propeller. The Wright brothers designed and tested aerodynamic propellers, and made the first powered flight in 1903 (Figure 1. a). Propellers were the first means of powering airplanes, preceding all other means of propulsion by about 40 years. This aeronautical propulsion system was used extensively through 1940's.

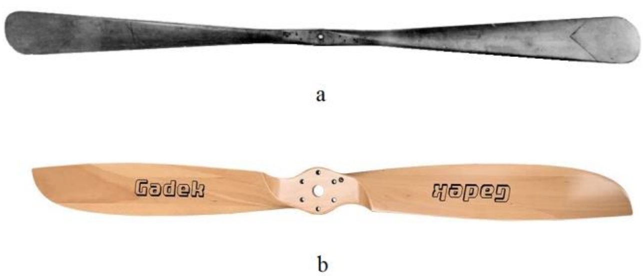

Figure 1: Wright brothers' propeller, b. Gadek propeller (2019).

Although there have been many refinements to propellers through the years, the general appearance of the propellers has changed little (Figure 1). An aircraft propeller can be described as an open, rotating and bladed device [2]. Today, a renewed attention is being focused on the first aeronautical propulsion device - the propeller. This is due to the increased use of unmanned aerial vehicles [3], the growing market of general aviation, the increasing interest in ultra-light categories or light sport air vehicles, and the growing importance of environmental issues that have led to the development of all-electric emissionless aircrafts [4].

One of the most disturbing problems of propeller-driven aircraft was and still is their noise, which may limit the aircraft's operation. On the whole, the frequency range for human hearing, commonly referred to as audio frequencies, is typically cited as approximately 20 Hz – 20 kHz [4]. And while the human ear is sensitive to sounds between 0 and 140 dB, the sound level (140 dB) is too painful to the listener [5]. In propeller-based propulsion systems, the main sources of noise are the engine and the propeller. Propeller aircraft noise reduction has been studied since the early days of aviation. Initially the need for noise reduction was coupled with the need for reduced detectability in military operations [6]. Noise generated by aircrafts can propagate into the airport neighborhood and into the aircraft interior causing annoyance and discomfort of residents and passengers [7]. For example: the noise generated from the propeller of the aircraft XF 84 H was 135 dB and reportedly heard as far away as 40 km. This aircraft was not very popular with pilots. The propeller – driven strategic bomber Tu – 95 is considered to be the noisiest flying machine in current world aircraft. US submarines can detect the aircraft flying high overhead through their sonar domes while still underwater.

The acoustic signature of military aircraft has a significant effect on their detection. The importance of noise signature of propeller-driven air vehicles was already noticed during the 1960s [8]. Today, with the increased use of propeller-driven vehicles, there is a renewed interest in reducing the noise of propellers [9]. Many airports around the world impose strict limitations on noise level permitted during day or night.

One of the most commonly known methods of reducing aero acoustic noise is a blade geometry modification. It is well known, that different parameters in details among various designs, such as number of blades, blade shape, propeller diameter, blade pitch, trailing edge geometrical modifications and propeller blade fineness have impact on acoustic noise [10]. The propeller noise can be reduced by increasing blade sweep, reduction of blade thickness and reduction of tip speed [2].

1.2 Porous wing scale of *lepidopterans*

Bio mimicry, sometimes called bionics, is the application of biological processes and forms found in nature to the study design of engineering systems [11]. Butterflies and moths both belong to the insect order *Lepidoptera*. These insects are usually called *lepidopterans* [12]. The surface of the wings of the *lepidopterans* is covered with millions of tiny movable appendages – scales (30-200 μm in size) [13] (Figure 2. a, c). In contrast to the butterflies, all body parts (a head, a thorax and an abdomen) of the moths are covered with abundant appendages (scales and micro bristles) (Figure 2. c, d). It is well known that the *lepidopterans* scale coverage reduces the potential of the reflected ultrasound signal from a flying moth [14 - 17], minimizes the noise [18] and the vibration in flying insects [19]. When an ultrasound wave strikes the *lepidopterans* surface, so significantly part of bat's calls and noise of a flying insect are transformed into heat in the pores of the scale coverage [14, 16, 17]. This way, the property of the coverage allows the insect to overcome predator's attack at night. These facts motivated the work presented in this paper.

The micro – and nanostructure of the *lepidopterans* wing scales is a true miracle of nature. Each scale of the butterfly *Papilio nireus* resembles dorsoventrally flattened sacs with an upper UL (also called obverse) and lower LL (also called reverse) lamina (Figure 2. b). The region between the upper UL and the lower LL lamina is termed the lumen Lu. The structure of the reverse lamina is generally undifferentiated. Both surfaces of this lamina are smooth, whereas the obverse lamina (Figure 2. b) possesses an intricate architecture, typically is composed of a series of longitudinal ridges Lr and of a porous structure (PS). The porous structure of UL has porosity values over 60 – 70 percent; the pore diameter is 240 nm, the scale thickness (without ridges Lr) is 3 m [20].

The upper lamina of the porous scales of the butterfly *Delias nigrina* (Figure 2. c and d) is a complex structure. This

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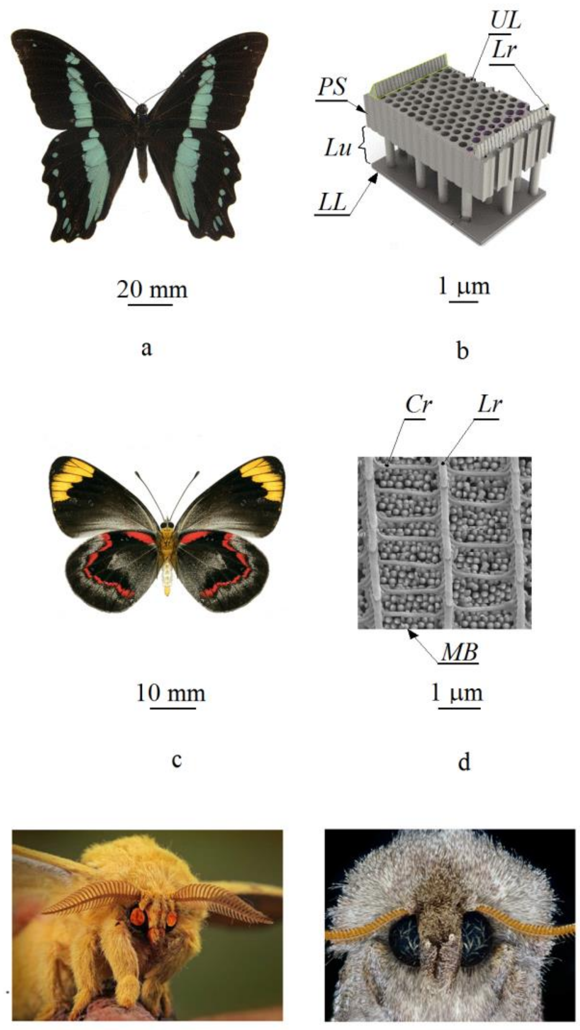
lamina composed of a series of longitudinal ridges and a series of cross ridges (CR). Longitudinal ridges and cross ribs frame open pores to the scale interior. The obverse lamina (Figure 2. d) has porosities from 40 to 50 per cent; the average size of the open pores is 1×1 μm. The lumen Lu of the porous appendages are abundantly studded with micro beads (MB) (Figure 2. d [22]). This type of porous structure has been classified as 'pigment granules' [22]. Every micro bead is elongated micro ovoid with dimensions of 100-500 nm [22]. This porous structure has porosity values over 30-40 percent, the scale thickness (without ridges Lr) is 1.5 μm.



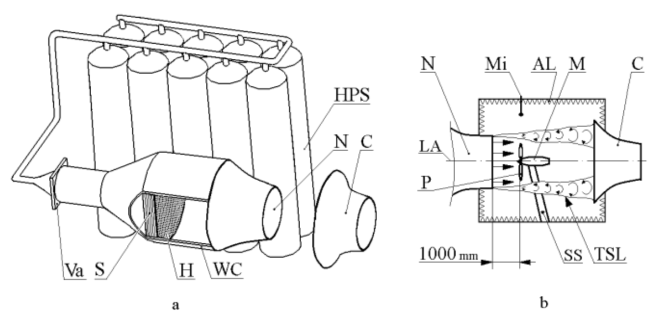
CR - cross ridges; *LL* - lower (reverse) lamina;
Lr - longitudinal ridges; *UL* – upper (obverse) lamina;
Lu – lumen; *MB* - micro beads; *PS* - porous structure.

Figure 2: a. Dorsal wing surfaces of butterfly *Papilio nireus*. b. Nanostructure (vertical cross-section) of a cover porous scale of *Papilio nireus*, drawn in 30 ° isometric [20, 21]. c. Dorsal wing surfaces of butterfly *Delias nigrina*. d. SEM showing a plane view of cover porous scale of *Delias nigrina*. The scales are studded with pigment granules MB [22]. e. A moth of *Saturniidae* family, f. A front view of a moth's head (*Noctuoidea* family).

2 Material and experimental methods

2.1 Wind-tunnel

The aero acoustic features of low-speed propellers were tested in the Zaporozhe Machine-Building Design Bureau (ZMBDB) low speed straight through a wind-tunnel (Figure 3). Air was driven from a high pressure storage HPS through the valve Va into a wide chamber WC with a low velocity. A screen S of wire gauze helped to equalize the velocity, across the cross-section of the chamber. A honeycomb H ensured that there was no large-scale swirling around in the channel, and that the air traveled along it in straight lines. The irregularity of wind of the wide chamber was swamped by the large space. Thus a uniform increase in velocity that occurred when the air passed through the narrower nozzle N (diameter of 2000 mm) was attained. A contraction section of the nozzle was designed using a matched pair of cubic curves. Thus, the airstream in the working section was uniform (the drift of the free stream velocity was less than about 0.9 %) and laminar (the free stream turbulence level was less than 0.5 % of the free stream velocity). The air speed of the wind tunnel was 30 m/s. One typical Reynolds based on chord length on this wind speed was 200000.



AL – Acoustic lining; P – propeller; Mi –microphone; M – motor; C – collector; H - honeycomb flow straightened; HPS - high pressure storage; N - nozzle; S – screen; Va – valve; WC - wide chamber; TSL - turbulent shear layer; SS - supporting strut; LA - longitudinal axis of the wind-tunnel.

Figure 3: a. Axonometric view of the ZMBDB wind tunnel, b. Transverse view (along the longitudinal axis LA) of experimental apparatus installed in the ZMBDB wind tunnel open test section.

Test section winds were measured using a Pitot-static tube connected to a Datametric Barocel Electronic Manometer. Pressure differences down to 0.0001 in H2O could then be measured. Turbulent velocity data and mean speed were also measured by using a constant temperature hot-wire anemometer. Air temperature was maintained at 20 ˚C.

All aero acoustic tests were carried out on two bladed propellers in the square anechoic room (length was 6 m, width was 4 m, and the height was 3 m) lined with absorptive acoustic wedges. Room location was at the Research Center of ZMBDB. The energy cut-off of the anechoic wedges had a sound absorption coefficient at normal incidence greater than 0.99. The collector was downstream of the test section. Noise-absorbing furry materials were attached to the surface of the collector to reduce the interaction noise between the open jet and the collector. The background noise was about 34 dB at a free stream velocity of 30.0 m/s. Figure 3 shows a picture of the chamber and a sketch of the layout of the experimental setup.

The measurements of noise were made during the evolution of the low-speed propellers in the square anechoic room. The acoustic instruments were produced by Brüel & Kjær and consisted in a sound and vibration analyzer Pulse-X3570 integrated with FFT and CPB analysis tools, a Nexus 2690 amplifier and 1 free field ¼" microphones type 4939 with a dynamic range of 28 Hz to 164 kHz, 200 V polarization. The sensitivity calibrated at 250 Hz by using piston phone type 4228 with ¼" adaptor DP 0775. The narrowband sound pressure level spectra were computed with a Fast Fourier Transform size of 8192, giving a frequency resolution of 0.2 Hz. The sampling frequency of acoustic instruments spans from 0.026 Hz to 28 Hz, depending on the maximum frequency to measure, and on the number of lines of discretization. In these measurements the author has adopted a resolution in the range 0.026 – 0.25 Hz, which guarantees a quite sharp definition of the acoustic discrete tones. The temperature and humidity inside the anechoic room were recorded to enable computation of the atmospheric absorption. The sound pressure levels (SPL) spectra were corrected for actuator response free-field correction, and atmospheric absorption. The overall sound pressure level (OSPL) was calculated through integration of SPL spectrum.

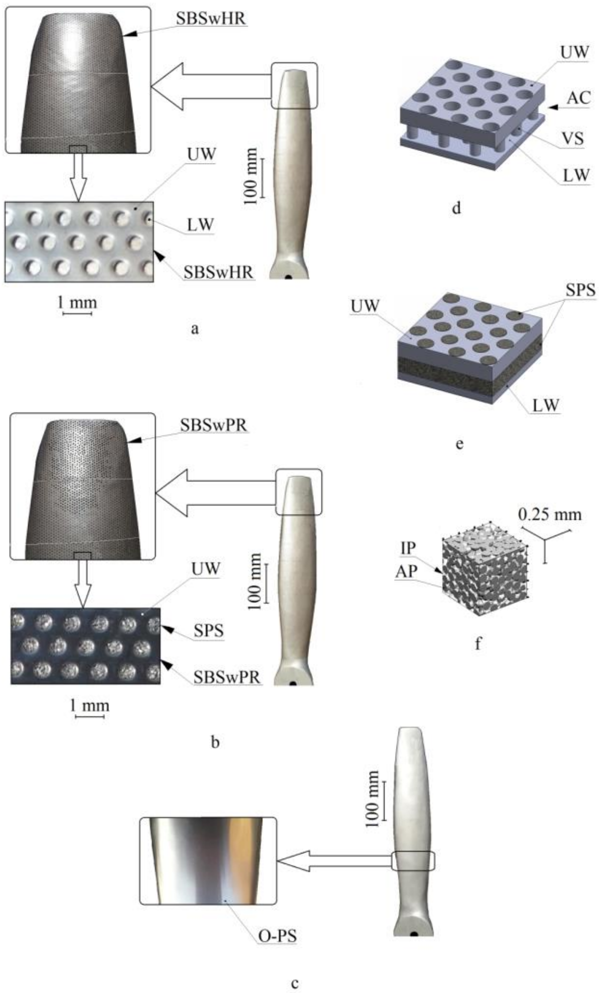
Previous theoretical predictions [23, 24] and experimental researches [25] showed that, when the observer/microphone moved from the axial location toward the rotation plane, the harmonic contribution of propeller noise became more evident, while the broadband term decreased, and then eventually the harmonic contribution dominated over the other contributions in proximity of the rotational plane. Following these conclusions, the microphone was attached to the anechoic room ceiling and lay in the intersection of two planes: the rotation plane and the vertical plane along the longitudinal axis of the wind-tunnel. The sensor was placed out of the air stream one diameter from the center of the propeller rotation, and the microphone locations were outside of the turbulent shear layer TSL. The position of the microphone relative to the propeller is shown in Figure 3.

The propellers were driven by an electro motor M, which provided a power of 102 kW at a rotational speed of 1780 rpm (revolutions per minute). The motor pylon was mounted to an aerodynamically shaped strut SS which was securely anchored to the floor by means of steel tracks embedded into it (the floor and the supporting strut were then covered with acoustic foams). Power was supplied by a 240 V three-phase electrical bus and controlled from the observation room. This allowed the experimenter to operate both the data acquisition software and experimental apparatus from one location set in an adjacent room where a designated control desk was set. The motor controller of choice was selected due to its external display (indicating motor rotational speed) and compatibility with an external potentiometer used to finely adjusts the motor's revolutions per minute. In order to mount the propellers on the shaft of the motor, an aluminum adapter was produced, to ensure that the ambient noise, which also includes the noise from the electrical motor itself, is not excessively high. The total sound pressure level of the motor was 39 dB at a free stream velocity of 30.0 m/s. A set of measurements was taken with the free electrical motor alone, and it was found that for rotational speeds exceeding 1780 rpm the background noise was small.

2.2 Propellers

Three different propellers were used (Figure 4. a, b and c). The skin of first propeller (Figure 4. a) imitated the cover hollow wing scale of the *Papilio nireus* butterfly (Figure 2. b). This skin called Smooth Butterfly Skin with a Hollow Region (SBSwHR) (Figure 4. a) was 400 times life size (the thickness was 1.2 mm) (Figure 4. a, b). SBSwHR was composed of two layers. The upper metal wall UW (the thickness was 0.5 mm) and the lower metal wall LW (the thickness was 0.2 mm) were separated by an air cavity AC (0.5 mm in clear spacing) Figure 4. d). Both metal layers were joined by vertical supports VS. The facing surface and opposite side of the UW were smooth. The external wall (UW) provided with diagonally staggered rows of round perforation (hole diameter was 0.5 mm). The porosity of the UW was 40 %. This metal wall was manufactured by ANDRITZ Fiedler Company. The lower metal wall LW was similar to a thin sheet. Since, the propeller blade shape was very complex and different, the blade was made with eleven butterfly skin segments. The butterfly skin segments were formed around the blade. Initially, every segment was supported by the propeller body and was affixed on the smooth outer surface of the propeller blade. Then, the segments were disposed very close to each other. Finally, every abutment joint was covered with glue putty and was formed a flush joint.

The skin of the second propeller imitated the cover porous wing scale of the *Pieris rapae* butterfly and the cover porous wing scale of the *Delias nigrina* butterfly (Figure 2. c). This skin called Smooth Butterfly Skin with a Porous Region (SBSwPR) (Figure 4. b) was 800 times life size (the thickness was 1.2 mm) (Figure 4). SBSwPR was composed of free layers (Figure 4). The experimental studies by Pechan and Sencu [26] and by Hamacawa et al. [27] showed that various surface imperfections (groove, ridge, et cetera) of the propeller blade [26] or of the airfoil [27] may generate the noise. So, the faicing surface and opposite side of UW were smooth. The upper metal wall UW of the SBSwPR was geometrically similar to the UW of the SBSwHR. The lower metal wall LW was similar to a thin sheet. The air hole between UW and LW and the round hole perforations of the UW were filled with porosity material. The sintered powder stuffing SPS was manufactured by ZMBDB. The thickness of the UW was 0.5 mm, the thickness of the SPS was 0.5 mm and thickness of the LW was 0.2 mm. The aluminum powder AP sizes were in the range of 50 µm to 65 µm, and inter particle porosity IP was 35 % (Figure 4. f). The facing surface of the UW was disposed flush the exterior surface of the powder stuffing (Figure 4. l). The sintered production process is described in detail in work [28]. A brief description of this process is submitted follows.



SBSwHR: UW - upper metal wall; AC - air cavity;
VS - vertical support; LW - lower metal wall;
SPS - sintered powder stuffing;
SBSwPR: smooth butterfly skin with a porous region;
AP - aluminum powder; IP - inter particle porosity;
O-PS - one-piece skin.

Figure 4: Front view of three propellers. a. propeller with SBSwHR, b. propeller with SBSwPR, c. propeller with one-piece skin, d. a vertical cross-section of the smooth butterfly skin with a hollow region in axonometric plane, e. a vertical cross-section of the smooth butterfly skin with a porous region in axonometric plane, f. 3D computer tomography of the sintered powder stuffing in axonometric plane.

Initially a hydraulic press, cold-molding die was made. Then, an aluminum powder with an incorporated amount phenolic binder was poured into the die. Next, the die assembly was jogged to settle the powder, and baked at 230 °C to cure the phenolic binder. Finally, the stuffing was removed from the die in the molded-and-cured form ready for sintering. The stuffing was sintered at 560 °C for four hours in vacuum of 1×10^{-6} to 1×10^{-7} Torr. This sintered process used the alumi-num powders, which were manufactured by Valimet Inc. Similar to the first propeller which the SBSwHS, the blade of second propeller was made with eleven segments of the SBSwPR (Figure 4. b). Similarity these butterfly skin seg-ments were formed around the blade, and as well each seg-ment affixed on the smooth outer surface of the second propeller blade, and were disposed very close to each other, and formed a putty flush joint. For the structural design of the SBSwPR there are not equivalents in the modern porous media.

Since the SBSwHR and the SBSwPR imitated the cover wing scales of one order – *Lepidoptera*, so the author incur-porated both these skins (SBSwHR and SBSwPR) into one group – ‘butterfly acoustical skin’ - BAS.

It is the principal concern of this study to qualitatively determine the effect of butterfly skin on the rotating propeller acoustic. Therefore, the metal skin (O-PS) of the third propeller was one-piece, smooth and airproof. The skin thickness was 1.2 mm. The blades of the third propeller were hand-finished (Figure 4. c) to highly smooth and polished surfaces, using 12000 - grit sand paper. The skin was chaped around the blade, and was affixed on the smooth outer surface of the third propeller blade. All the three propellers had identical geometric parameters: airfoil sections (NACA 2415), diameter (1200 mm), thickness, chord and pitch. The acoustical properties of the third propeller were compared with that of the first and second propellers.

3 Results

This section presents the acoustic results for the three propellers. The discussion focuses on the blade passing frequency (BPF) tones of these propellers. Figure 5. a, b and c corresponding to the blade skin displayed in Figure 5 for rotational speed 1780 rpm. The frequency along the horizon-tal axis ranges from 0 to 3,800 Hz, covering both the narrow-band and the broadband parts of the total noise. The harmonic part is shown in the lower frequency range (e. g. from 0 to ~3,250 Hz for smooth skin in Figure 5. a, and from 0 to ~2,200 Hz for hollow skin in Figure 5. b). The tonal noise levels represent most of the contribution to the total noise (Figure 5. a and b), while the broadband noise represents only a small portion.

Initially, the author examined the smooth rotating propeller acoustics. Figure 5. a displays the near field narrow-band SPS spectra in the rotor plane. In this plane the fundamental BPF ton 1 and its higher harmonics up to tone 6 is dominant. The peak of the tone 1 is 25 dB above the broadband noise. Figure 5. a shows that rotating propeller generated tones at harmonics of 567 Hz at high levels over 65 dB extending from low frequencies to approximately 2,700 Hz. These rotating propeller tones begin at 82.6 dB and drop to approximately 63 dB at 3,250 Hz. The total sound pressure level OSPL of the rotating propeller with the smooth skin, which takes into account the entire frequency domain (0…100 kHz), is 56.5 dB.

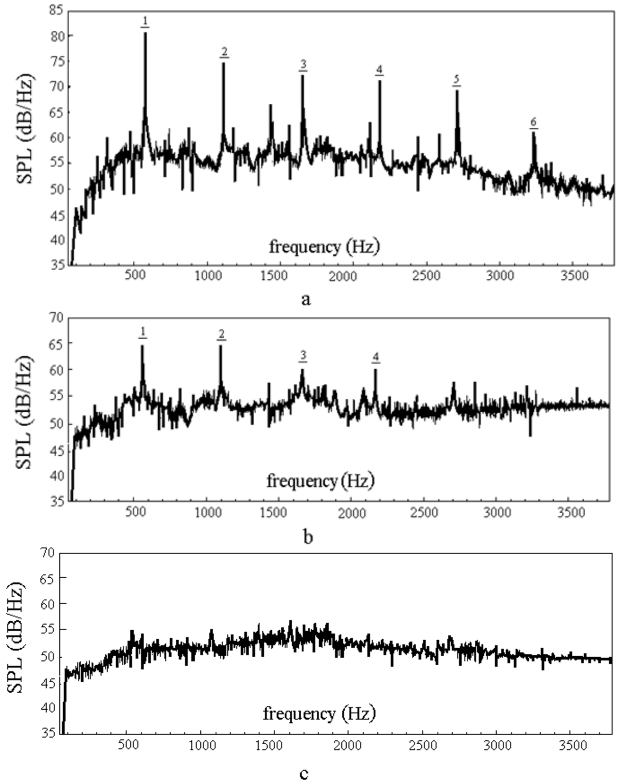


Figure 5: Near field SPL spectra for the rotating propeller with smooth skin (a), hollow skin (b) and porous hollow skin (c).

Then, the author examines the impact of the hollow skin on rotating propeller acoustics. Figure 5. b plots the near field noise narrow band and broadband SPL spectra from rotating propeller with the hollow skin in the rotor plane. Multiple peaks are observed on the spectrum. Examining the spectrum the author clearly distinguishes tones 1, 2, 3 and 4. The author observes a temperate content of tones, with the principal ones labeled. The fundamental BPF tones 1 and 2 are dominant and have similar magnitude. The next stronger tones 3 and 4 are about 3 dB lower than the dominant tones. Higher harmonics 5 and 6 are buried in the broadband noise. The maximum peak level of the spectrum is approximately 18.6 dB lower than the higher harmonic 1 of the propeller with the smooth skin at 567 Hz. Therefore, this skin is effective to reduce the tonal noise from the rotating propeller. On the other hand, the broadband noise is slightly increased from 2,300 Hz to 3,800 Hz for the rotating propeller with hollow skin (Figure 5. b). One of the main mechanisms of generating higher amplitude broadband noise is the turbulent boundary layer flow developing over the porous outer surface of the hollow skin. The skin increases the velocity disturbance in the boundary layer on the porous outer surface of the rotating propeller, and increases the turbulent noise [29]. The total sound pressure level OSPL of the rotating propeller with the hollow skin, is 54.2 dB. A quantitative comparison of the sound pressure levels shows that the total sound level of the rotating propeller with the hollow skin is more than 2 dB lower with respect to the one with the smooth skin. This result compares well with the noise reduction of a stator vane by passive porosity [30].

Finally, the author examines the impact of the porous hollow skin on the rotating propeller acoustics. Figure 5. c displays the near field noise from rotating propeller with the porous hollow skin in the rotor plane. No peaks are formed in the spectra – all harmonics are buried in the broadband noise. The broadband part dominates over the other contributions in the rotor plane. Based on the spectra results (Figure 5. c), it seems that the most effective mechanism of reducing the acoustic waves in the harmonic part of the noise spectrum is the rotating propeller with the porous hollow skin. Moreover, Figure 5. c shows a slight decrease in the broad band noise level from 2,300 Hz to 3,800 Hz for the propeller. It is clear that the porous hollow skin is more efficient in reducing broadband noise than the hollow skin. This suggests that the porous diameter of the porous hollow skin (0.1 mm) is less efficient in exciting the turbulent noise than the one of the hollow skin (0.5 mm). The total sound pressure level OSPL of the rotating propeller with the porous hollow skin, is 52.5 dB. A quantitative comparison of the sound pressure levels shows that the total sound pressure level of the rotating propeller with the porous hollow skin is more than 1.5 dB lower with respect to the one with the hollow skin and is more than 4 dB lower with respect to the one with the smooth skin. The latter result compares well with the noise reduction of the porous-bladed fan given by Chanaud at al [31].

4 Discussion

4.1 Propeller noise reduction

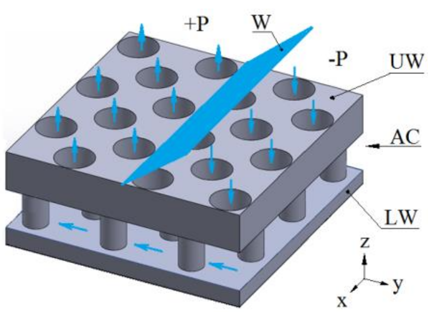
The major propeller noise components are thickness noise (due to the volume displacement of the blades), steady-loading noise (due to the steady forces on the blades), unsteady-loading noise (due to circumferentially nonuniform loading), quadrupole (nonlinear) noise, and broadband noise [32]. Each one of these components acts on the blade surfaces.

Noise absorption mechanism of propeller with SBSwPR

Sarradj E. and Geyer [29] showed the noise reduction mechanism by porous airfoils. The author developed the mechanism of propeller noise reduction by SBSwPR on the basis of Sarradj's and Geyer's mechanism. Noise absorption of a propeller with SBSwPR follows three aspects. The first of these aspects is acoustic absorption. Sintered powder stuffing of SBSwPR contains through pores and micro channels so that sound waves are able to easly enter through them. When sound enters the stuffing, owing to sound pressure, air molecules oscillate in the interconnecting voids that separate the micro granules with the frequency of the exiting sound wave. This oscillation results in frictional losses. A change in the flow direction of sound waves, together with the expansion and contraction phenomenon of flow through irregular pores, results in a loss of momentum. Owing to the exciting of sound, air molecules in the pores undergo periodic compression and relaxation. This results in change of temperature. Because of long time, large surface to volume ratios and high heat conductivity of powder stuffing, heat exchange takes place isothermally at low frequencies. At the same time in the high frequency region compression takes place adiabatically. In the frequency region between these isothermal and adiabatic compression, the heat exchange results in loss of sound energy. So, the reasons for the acoustic energy loss when sound passes through sound absorbing materials are due to: frictional losses, momentum losses and temperature fluctuations [33, 34]. Another possible aspect is the dissipation of turbulent energy from boundary layer by the porous surface. This would also result in less broadband noise generation at the trailing edge. The third aspect is the reducing influence on noise generated by the contact of turbulence with leading edge and also on other noise generation components. In addition, scattering of the micro granules also influences the absorption of sound energy inside the powder stuffing

Propeller noise reduction mechanism by SBSwHR

It is well known, that fan noise reduction can be achieved either by design aiming for it at the source or by incorporating acoustic treatment to absorb the noise produced by the source [35]. Approaches to reduce noise at the source are based on the fact that any of the significant noise generating mechanisms is related to unsteady, periodic forces acting on the surfaces of rotating fan, and caused by gust-type disturbances. These unsteady forces give rise to acoustic perturbations that propagate through the fan duct and radiate as noise. The noise level generated from this source is directly proportional to the magnitude of the fluctuating lift force. Thus, any reduction in this fluctuating force would result in a reduction in noise.



AC – air cavity; W – sound wave; UW – upper wall;
LW – lower wall; +P – high pressure region;
-P – low pressure region

Figure 6: The influence of the sound wave W on the SBSwHR, drawn in axonometric.

Tinetty A.F. et al. [35] shows the mechanism to reduce interaction noise in turbo machinery by passive porosity on the stator vane. The author developed the mechanism of a propeller noise reduction by SBSwHR on the basis of Tinetty's mechanism. Figure 6 shows a schematical drawing of what may be assumed to happen. In Figure 6 plotted a local sound wave W in (Y-Z-X) plane around a fragment of SBSwHR in an axonometric view. A rotating propeller produces unsteady and periodic forces acting on the porous outer surface of SBSwHR, which result in sound wave radiation. The sound wave produces the high-pressure region +P and the low-pressure region –P on the upper wall (UW). The regions with a pressure difference are connected by porous of the UW and by the air cavity AC. Therefore, the air is transfered through the AC in a direction from the high-pressure region +P to the low-pressure region -P. Thus, the pressure difference between the two regions is redistributed and is reduced. For this reason the propeller noise is decreased.

Thus, 'butterfly acoustical skin' will become a very effective means to improve acoustic performances of the propeller-based propulsion systems. A higher acoustical performance of propeller blades with BAS can improve flying quality, safety, and comfort of passengers and residents of airport neighborhood. It can reduce detectability in military operations (detection of an aircraft with this propeller by an enemy's passive acoustic system can be difficult). In addition to the aircraft, the butterfly skin could also be used in jet engines and in submarines.

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CHARACTERISTICS OF A CAVE-STYLE TRADITIONAL STAGE IN SHANXI PROVINCE, CHINA

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Résumé

Les scènes traditionnelles chinoises sont uniques dans l'histoire des théâtres antiques. Elles ont donc une grande valeur pour la recherche des caractéristiques acoustiques de scènes. Parmi les nombreuses scènes traditionnelles chinoises, les scènes en forme de grotte et murs en écailles de la province du Shanxi ont des effets acoustiques particuliers, qui sont simulés dans cet article à l'aide d'une approche temporelle à différences finies. Une technique conventionnelle combinée à des couches parfaitement adaptées est introduite dans les différences finies de l'équations d'onde prisent dans le domaine temporel. Cela permet de résoudre le problème acoustique d'une limite courbée en espace ouvert. Pour vérifier la validité du modèle temporel à différences finies, des valeurs simulées sont comparées à des valeurs mesurées. De plus, la distribution de la pression acoustique est simulée pour plusieurs modèles de scènes de type caverne et murs écaillé. En fonction des réponses impulsionnelles, plusieurs paramètres acoustiques de la pièce, tels que l'intensité sonore, la clarté et le temps de réverbération, sont analysés. Enfin, un test d'écoute basé sur une méthode de comparaison par paires est effectué.

Mots clefs : Chinois, scène traditionnelle, style grotte, mur d'écailles, domaine temporel à différences finies, acoustique, frontière courbe

Abstract

Chinese traditional stages are unique in the history of the world's ancient theaters, so they have significant meaning in research on their acoustical characteristics. Among the many Chinese traditional stages, the cave-style stages and splay walls in Shanxi Province have special acoustic effects, which are simulated using a finite-difference time-domain approach in this paper. The conformal technique combined with perfectly matched layers is introduced into finite-difference time-domain equations for sound waves, which solves the acoustic problem of a curved boundary in open space. To verify the validity of the finite-difference time-domain model, simulated values are compared with measured values. Furthermore, the sound pressure distribution of several cave-style stage models and splay walls are simulated. According to the impulse responses, several room acoustical parameters, such as loudness, clarity and reverberation time, are analyzed. Moreover, a listening test based on a paired comparison method is conducted.

Keywords: Chinese, traditional stage, cave-style, splay wall, finite-difference time-domain, acoustic, curved boundary

1 Introduction

Ancient theatres have been investigated for several decades in some fields, including architecture, archaeology, drama and acoustics [1]. However, most of these acoustic researches are on ancient Greek and Roman theatres [2-4], and very little on traditional Chinese theatres.

In ancient Chinese buildings, acoustic buildings are mostly attached to other architectural types, which can be divided into open-air theatres, courtyard theatres and indoor theatres, for example [5]. The courtyard theatre is the most important form of ancient Chinese acoustic buildings. In addition to their important historical and cultural value, ancient Chinese acoustic buildings also contain the ancient Chinese understanding of architectural acoustics and the application of architectural acoustics technology. The study of ancient Chinese acoustic buildings has a positive significance for us to understand the architectural wisdom of the ancient Chinese and better use the principles and techniques of modern architectural acoustics.

A few scholars have carried out preliminary research on ancient Chinese acoustic architecture in China [6, 7]. However, most of these studies are from the perspectives of history, culture, architectural structure, building repair and protection, and seldom from the architectural acoustic point of view. Due to reasons of culture, history and climate, most of the remaining ancient Chinese acoustic buildings are in Shanxi Province. There are many cave-style stages in the middle and the west of Shanxi Province. The structure of this kind of stage is related to the cave buildings where the local people live, and its structure is similar to the coupling space in the hall, which has certain significance to exploring its acoustic properties. Since the Qing Dynasty, the architectural form of the traditional stages has tended to mature; meanwhile, traditional stages in Shanxi Province with splay walls on two sides of the stage mouth became popular. The shape of splay walls is various and their sizes are different; furthermore, the splay walls are set at the stage mouth similar to the reflected boards at the modern stage mouth, which not

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only beautifies the stage but also improves the sound quality of the stage.

Ancient Chinese acoustic buildings have some characteristics. They are mostly open space or roofless, making it difficult to describe the acoustic characteristics using traditional acoustic parameters. A majority of ancient Chinese acoustic buildings fail to be preserved because of the climate, wars caused by dynasty change and other reasons, which makes measurements impossible. However, we can refer to historical materials to restore the sizes of the building structures, obtain the acoustic characteristics through measuring the sound absorption coefficient, and then build computational models. Currently popular acoustic simulation software includes EASE, Odeon, CATT and so on [8, 9], but they can only simulate large space acoustics and high frequency sound. For low frequency and small room acoustics, wave acoustic method is required. The space dimensions of ancient Chinese acoustic buildings are generally not large, so it is suitable to apply a computer research method based on wave acoustics.

The research methods based on wave acoustics mainly include the finite element method [10], the boundary element method [11], and the finite-difference time-domain method (FDTD) [12, 13]. The first two methods are calculated in the frequency domain first and then converted into time domain results, which are more complex. FDTD is based on the numerical calculation of the time domain, whose calculation is simple, and the sound field distribution can be calculated. In this paper, we build several kinds of cave-style models to compute the impulse response of receiving points through FDTD. The cave-style stages are curved boundary and the splay walls are tilt boundary, which cannot be represented in a Cartesian grid. The curved boundary, which is traditionally represented in a stair-step fashion, has a low accuracy [14], hence a locally conformal technique is used to solve the curved boundary. The acoustical parameters such as loudness and clarity are analyzed from the impulse response. At the same time, a subjective evaluation test is carried out to verify the parametric analysis and study the sound effect of cave-style stages.

2 Numerical methods

In a Cartesian grid, the three-dimensional acoustic wave equation and the continuity equation in an ideal air medium are discretized with finite differences [15]. The finite-difference scheme for these equations in a uniform staggered grid can be written as difference equations (12)-(15) in reference [16]. Generally, the space step Δh is less than one tenth of the wave length λ to guarantee the computational stability; that is, $\Delta h \leqslant \lambda/10$. Meanwhile, the time step and space step should also satisfy the stability condition shown as the equation (18) in reference [16]. In this paper, the space step Δh was set to 0.07 m; thus, the time step Δt was set to 117 μs.

2.1 Excitation source model

When there is a sound disturbance in a room, the propagation of sound waves in the room can be calculated recursively according to the wave difference equations. Temporal evolution of the sound pressure value observed at all time steps of a point in the room is the impulse response of that point. The sound pressure of all points in the room at a certain moment is the sound field distribution. To calculate the impulse response of the receiving point, the sound source is generally set as the derivative of a Gaussian function of equation (28) in reference [16], and the parameters were set to α=0.711 49×10^6, β=2.683 18×10^{-3} in this paper.

2.2 Boundary conditions

Impedance boundary

Limited by computer memory and computing time, when wave difference equations are used to recurse the sound pressure and vibration velocity of some point in the sound field, it needs to be limited within a certain space, which requires the corresponding boundary conditions. Boundary conditions are an important part of FDTD research. In the previous study, impedance boundary conditions related to the sound absorption coefficient are shown in reference [17].

Conformal-PML boundary

The actual building boundary is usually a curved surface, which is dealt with using the traditional method of stair-step approximation. As the approximation can cause some errors, locally conformal FDTD equations for a 3D acoustic wave motion with rigid boundaries were presented by Tolan [18]. The rigid boundary is treated by setting the particle velocity to zero. The walls of ancient stages are mostly made of black brick, with an absorption coefficient from 0.03 to 0.07. Since the absorption coefficient is very small, the building surfaces are treated as rigid boundaries. The ground, which is mainly mud, is set as an impedance boundary with the absorption coefficient of 0.2. In contrast to the rigid boundary, the perfectly matched layer (PML) absorption boundary completely absorbs the incident wave, which was used to simulate the free field boundary. The PML equations shown in reference [19] which can directly replace the wave difference equations.

The traditional stage is not a closed space; hence, the boundaries of these non-architectural interfaces can be treated as PML boundaries. Combining locally conformal equations [18] with the PML boundaries [19], the pressure update equation is obtained

$$p_x^{n+1}(i,j,k) = e_x^{(1)}(i,j,k)p_x^n(i,j,k) - e_x^{(2)}(i,j,k) \times [A_x(i,j,k)u_x^{n+1/2}(i,j,k) - A_x(i-1,j,k)u_x^{n+1/2}(i-1,j,k)]/V(i,j,k) \quad (1)$$

where u_x is gas particle velocity in x direction; p_x is the pressure of gas in x direction; the coefficient e_x is listed in reference [19]; $V(i, j, k)$ is the cell volume outside the rigid boundary, $A_x(i, j, k)$ is the area of a cell face outside the rigid boundary. Eq. (1) is the conformal-PML equation in x direction and the update equations in y and z directions are analogized.

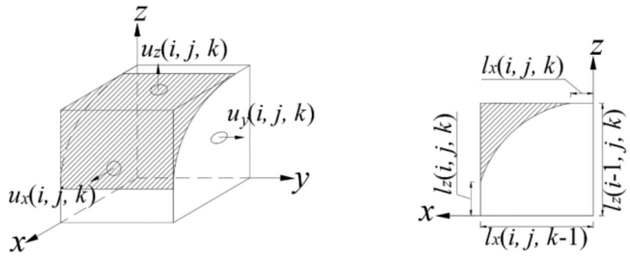


Figure 1: 3D conformal mesh and its projection. Left is a conformal grid cell and right is its projection on the *xoz* plane.

As Tolan suggested previously, the grid cell was subdivided into smaller subcells, and the total number of subcells were then counted to determine the area $A(i, j, k)$ and volume $V(i, j, k)$. This method is time-consuming and complex, therefore, in this paper, the volume and area of the boundary of the curved surface were calculated by the projection method shown in Figure 1. Setting the vault as a semicircle, we use the intersection between the equation of the semicircle and the grid to find the length of each edge $l_m(i, j, k)$, from which we can obtain the area $A_m(i, j, k)$ and volume $V(i, j, k)$ from the product between $A_m(i, j, k)$ and the grid length, where m represents one of the surface normal directions x, y, or z.

3 Site measurement and verification

There are hundreds of cave-style traditional stages in Jinzhong City, Shanxi Province. There are single-hole and multi-hole cave-style traditional stages, among which the four-hole-intersection style is the most complex. The front view of the traditional stage of Chaoshan Temple in Xiaohu Village, Pingyao County, Shanxi Province, is depicted in Figure 2. The stage is four-hole intersecting, and the internal structure of the backstage is shown in Figure 3. According to local residents, the original length of proscenium was 5 m, but now it has been removed and only a 2.2 m long proscenium is left. On the opposite side of the stage is a cave-style wing, on its right side is a living bungalow, and on its left side is a brick wall, which is enclosed on all sides.

Figure 2: Front view of the traditional stage of Chaoshan Temple.

Figure 3: Internal structure of the backstage.

3.1 Site measurement

With reference to international standard ISO 3382-1:2009 [20], a starting gun was used as the pulse sound source, and the sound source was located on the central axis of the stage at a height of 1.5 m from the ground. A convenient microphone was placed at the receiving point at a height of 1.3 m from the ground. Due to the symmetrical structure of the stage, the receiving points were only located on one side of the central axis of the stage, and there were 11 receiving points arranged at equal intervals. Audition software was used to record the measured pulse responses, and the yard was empty except for our three measurers during the measurement. The distribution of receiving points is shown in Figure 4.

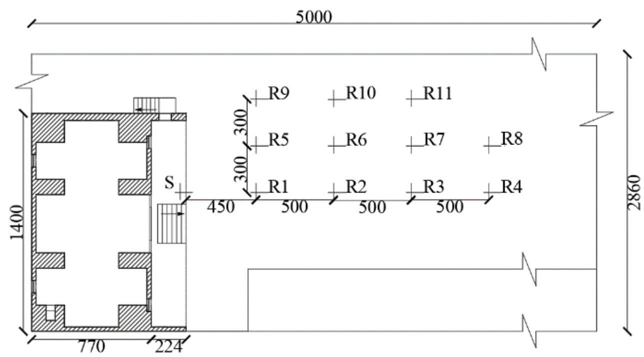


Figure 4: Distribution map of receiving points at the Chaoshan Temple stage, Xiaohu Village.

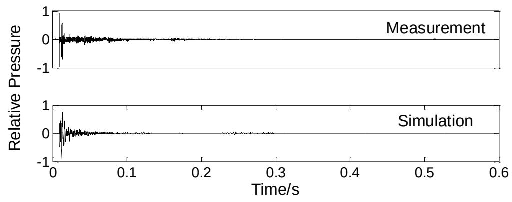
3.2 Simulation Model

According to the size in the distribution map of receiving points at the Chaoshan Temple stage, the simulation models containing the surrounding walls were established. Several trees in the yard were ignored in the model, and the houses in the yard were treated as brick walls. The ground was set as the impedance boundary with a sound absorption coefficient of 0.55, and the surrounding brick walls whose height was 2.1 m were set as the impedance boundary with a sound absorption coefficient of 0.11. To facilitate programming, the brick walls of the stage were set as the rigid boundaries. The sound source point and the receiving points were set as shown in Figure 4.

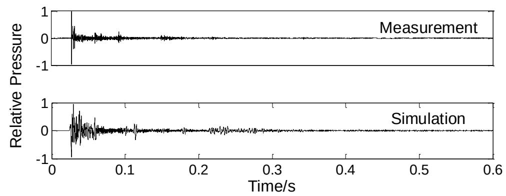
3.3 Comparison between measured and simulated results

The impulse response of each receiving point can be obtained after simulation calculations, and a receiving point was selected from each column to be compared with the measured results, as shown in Figure 5.

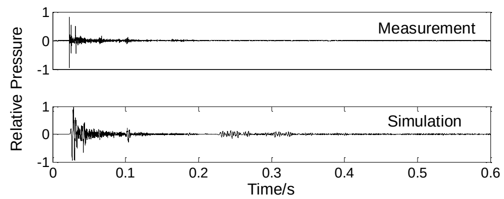
As Figure 5 shows, the sound pressure attenuation trend of impulse responses obtained by the simulation and the measurement are similar. Because the stage was set to a rigid boundary in the simulation model, the late reflected sound pressure of the simulated results caused by the cave backstage was bigger. On the contrary, the measured result of reflected sound pressure was small owing to air absorption and sound absorption of plants.



(a) Receiving point R1



(b) Receiving point R6



(c) Receiving point R9

Figure 5: The measured and simulated impulse responses of three receiving points.

Some parametric analyses were made to the impulse response of the 11 receiving points, their average was calculated and the measured and simulated results were listed in Table 1. From the data, the clarity C_{80}, the early decay time EDT, and the reverberation time RT of the measured results were basically consistent with the simulated results, which illustrated that the finite-difference time-domain method applied to the architectural acoustics was accurate and the boundary model set up in this paper was valid.

Table 1: Parameter analysis of measured and simulated results.

	C_{80} (dB)	EDT (s)	RT (s)
Measurement	10.75	0.63	0.78
Simulation	8.62	0.77	0.76

4 Subjective listening test

4.1 Experimental models

Based on the structure and size of the traditional stage of Chaoshan Temple, as well as literature and field trips, four stage models with different kinds of backstage structure were built. Model 1 had no cave in the backstage; that is, the hole was blocked with a wall. The backstage cave of Model 2 was vaulted with a single longitudinal cavity facing the auditorium. Similarly, the backstage cave of Model 3 was vaulted, with a two-hole-intersection style. Likewise, the backstage cave of Model 4 was vaulted, with three vertical and one horizontal cavity in a four-hole-intersection style. Model 4 was the model closest to the backstage of the traditional stage of Chaoshan Temple, whose 3D scenograph is shown in Figure 6.

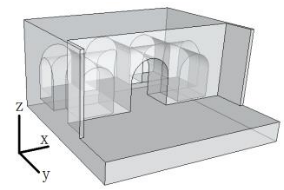


Figure 6: 3D scenograph of the ancient stage of Chaoshan Temple

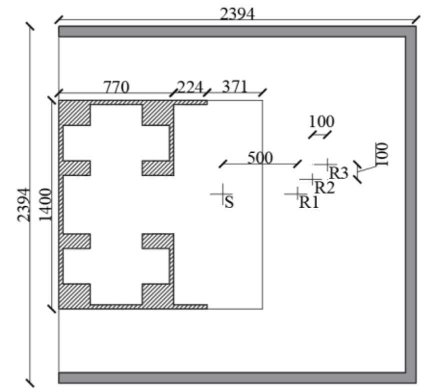


Figure 7: Positions of sound source point and all the receiving points in model 4. Dimensions in cm. The dark gray represents the PML boundary and the diagonal line represents the wall.

The computing space of the whole courtyard model was 23.94 m×23.94 m×7.49 m. There were two walls with a width of 2.52 m on both sides of the stage. The sound source point S was located on the central axis with a coordinate position of (11.97 m, 11 m, 3.01 m). The receiving point R1 with a height of 1.47 m was set in the auditorium 5 m away from the sound source; likewise, receiving points R2 and R3 were set at the same height of R1, as shown in Figure 7. The stage base is as high as these receiving points.

4.2 Listening test arrangement

To conduct the listening test, it is necessary to calculate the binaural impulse response of the listening position. Since it is very difficult to set the head model in the calculation model, in this paper two points with a distance of 0.21 m were taken as the left and right ear positions. As the spectrum of the excitation source was not straight, its impulse response, which was calculated by the finite-difference time-domain method, needed to be corrected. The sound sources selected from the signal library of Odeon software were convolved with the corrected impulse response to obtain the audio signals. Then, the audio signals were played through the headset for the test. Three sound sources that are similar to ancient Chinese opera were chosen for this test. The horn and flute are often used in the performance of ancient Chinese opera, and the soprano is close to the singing form of ancient Chinese opera. Therefore, we used Flugel's Amazing Grace and Bach's Badinerie and Soprano as sound sources, whose segments of 4 s, 5 s and 9 s were intercepted, respectively. The acoustic effects of the models were evaluated by the traditional paired comparison method. Any two models constitute a comparison pair; hence, each subject had to compare 90 pairs of signals of three receiving points.

The operation interface of the test was designed by Matlab GUI. The subjects wore headphones to complete the experiment on this interface and the data results were saved automatically. Four male and four female students whose age ranged from 21 to 29 were chosen to take part in the test. All of them had listening test experience. The test was conducted in a control room with ambient noise less than 40 dB. The AKG K702 headphone was used for listening, whose frequency response curve at 20 Hz~16 kHz is basically straight. On the operation interface, the sound signal of first model as A and the sound signal of second model as B were marked. The reference signal was labelled, which was copied from first model as A_0. The play order of A and B was generated randomly. Signals A, B and A_0 can be played after clicking. The subject was asked to choose the same signal as the reference signal A_0 between A and B, and judge the criterion, mainly from five subjective evaluation factors; that is, loudness, clarity, sense of space, sense of distance, and fullness.

Before the test, the subjects received the interpretation of acoustic evaluation indexes; in particular, reverberation sense and fullness. The formal test begins after several listening practices can be selected correctly. During the test, subjects were asked to listen to a signal at least three times. Subjects were forced to choose either A or B as much as possible, although they were allowed to choose nothing if they really could not hear the difference. Subjects clicked to play A_0, A or B until the final choice was made.

4.3 Results and Analyses

Acoustical parametric analyses

As the traditional stage is not an enclosed space, we considered the PML boundaries as walls with a sound absorption coefficient of 1 and then calculated the room impulse response. According to the room impulse responses, the sound quality of cave stages can be evaluated. In the performance of ancient Chinese opera, the volume should be large enough to deeply infect the audience. In this paper, we chose the sound strength G that is related to volume as the loudness indicator [21]. A Schroeder decay curve for each receiving point can be obtained by reverse-time integration of the squared impulse responses; from the decay curves, the reverberation time T_{30} and early decay time (EDT) can be calculated. The sound strength G, clarity, reverberation time and early decay time of each model calculated at three receiving points in the auditorium are listed in Table 2.

The results show that G of Model 2 is significantly larger than that of other models. The vertical cave can provide a sound energy supplement to the auditorium as a form of coupling space, which can enhance the value of G in the auditorium as well. Because the lateral cave retains a certain amount of sound energy, the values of G in Model 3 and Model 4, which have both a vertical cave and a lateral cave, are similar to that of Model 1 because the vertical cave provides a sound energy supplement to the auditorium, which reduces the clarity (C_{80}) of the latter three models. However, because the auditorium is open, the C_{80} of all models are positive; that is, the clarity of the auditorium is good. The values of reverberation time T_{30} of all models range from 1.70 s to 1.83 s, which are larger than the optimal value proposed by Barron [22]. The optimal value of reverberation time proposed by Barron is for modern closed theatre halls, while most traditional Chinese stages are not closed; therefore, the optimal value does not fit here. T_{30} of Model 1 is larger than the latter three models; however, the reverberation time of the latter three should be larger because there are vertical caves in their backstage providing an acoustic energy supplement, which can enhance the sense of reverberation. Therefore, reverberation time T_{30} is not accurate to describe the reverberation of ancient Chinese stages. Another indicator related to reverberation time is the EDT, shown in Table 2 for all models ranging from 0.96 s to 1.42 s. The values of EDT for the latter three models are larger than that of Model 1, and they are smaller than their corresponding T_{30}, so the EDT can better explain the reverberation sense than T_{30} for open ancient stages.

Table 2: G、C_{80}、T_{30} and EDT of four models.

	Receiving point	Model 1	Model 2	Model 3	Model 4
G	R1	6.93	7.55	7.20	6.92
	R2	5.75	6.08	5.74	5.74
	R3	4.80	5.29	5.00	5.10
C_{80}	R1	6.87	5.24	5.48	5.32
	R2	5.44	3.78	4.87	4.55
	R3	4.34	3.24	3.83	3.34
T_{30}	R1	1.83	1.75	1.78	1.79
	R2	1.78	1.72	1.77	1.76
	R3	1.74	1.70	1.72	1.71
EDT	R1	0.96	0.98	0.96	0.99
	R2	1.25	1.42	1.28	1.37
	R3	1.25	1.29	1.37	1.4

Subjective listening results

Each time point compares a signal pair (a_i, a_j), where a_j acts as the reference signal. A score of 1 is given if the selected signal is consistent with the reference signal, while a score of 0 is given if the selected signal is wrong, while a score of 0.5 is given if the subject chooses nothing. The rate of accuracy can be obtained by dividing the total test number by the score of all subjects, and the results are shown in Table 3.

Table 3: Accuracy of the listening test.

a_j	a_i			
	Model 1	Model 2	Model 3	Model 4
Model 1	----	0.958	0.937	1
Model 2	0.042	----	0.791	0.889
Model 3	0.063	0.209	----	0.868
Model 4	0	0.111	0.132	----

After the data for all subjects are statistically analyzed, the accuracies of flute, horn and soprano are 0.88, 0.85 and 0.78, respectively. The accuracy of three kinds of material exceeds 0.7, while internationally accepted criteria for judging and evaluating test ranges from 0.6 to 0.7 [23], which shows that the species of listening materials had little influence on the test, and the results of the three materials were all effective.

The correct selection of subjective evaluation factors was statistically analyzed, as shown in Fig. 8. The probabilities of correct selection according to the sense of space and fullness were 0.69 and 0.74, respectively, which were in the range of the credibility index; however, the accuracy rate of the other three evaluation factors was lower than 0.5. This result shows that the effect of a cave-style stage on the sense of space and fullness was obvious, but the effect on loudness, clarity and distance was not obvious.

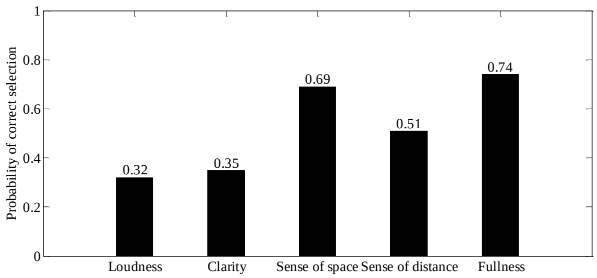


Figure 8: Probability of correct selection of five factors

The accuracy in the first row of Table 3 is above 0.937; that is, the latter three models with a cave backstage bring more fullness and sense of space than Model 1 without a cave backstage. By comparing the second and third rows in Table 3, the accuracy is almost above 0.8, which implies that the four-hole intersecting type and the two-hole intersecting type can be distinguished clearly from the single-hole longitudinal type; that is, it is easier to judge fullness and sense of space with the horizontal cave. In the last row of Table 3, the accuracy is 0.868, which shows that it is easy to distinguish the four-hole intersecting type from the two-hole intersecting type. Above all, the traditional stage with the four-hole intersecting type has the best fullness and sense of space. In parametric analyses section, the EDT of the latter three models is larger than in Model 1, which means that their reverberation and sense of space will be stronger. The subjective evaluation results are consistent with the EDT analysis in parametric analyses section, which further indicates that EDT is better than T_{30} to describe the reverberation of the traditional stage without a roof.

5 Splay walls

Since the Qing Dynasty, the traditional stages in Shanxi Province have been equipped generally with splay walls. Fig. 9 shows the traditional stage of Houtu Temple in Jiexiu City, Shanxi Province. The entablature has splay walls with a 1.4 m length above the stage on both sides (marked with red circles in Figure 9), and there is a 45-degree angle between the splay walls and the north-south axis. The structure of the splay wall is similar to the sound reflection boards in both sides of the stage mouth in a modern theater, which can gather sound and enhance the lateral reflection sound. The following part will discuss the acoustic effect of the splayed wall by establishing models according to the traditional stage of Houtu Temple.

Figure 9: Traditional stage of Houtu Temple in Jiexiu City, Shanxi Province.

5.1 Splay-wall models

At the ends of walls on both sides of the cave-style stages, connect the splay walls with a height of 3 m, a thickness of 0.28 m and a width of 3 m or 5 m. Due to the symmetry of the stage, it is enough to set receiving points on one side of the auditorium for investigation. The positions of 15 receiving points are shown in Figure 10.

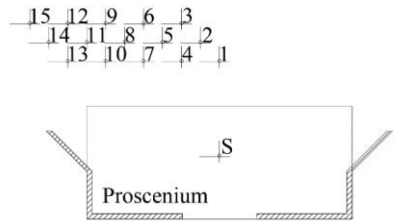


Figure 10: Coordinate positions of 15 receiving points in the auditorium.

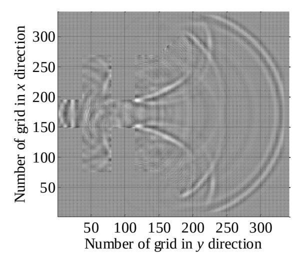


Figure 11: Waveform distribution of cave Model 3 with splay walls. At a height of 2.1 m above the ground, the sound source propagates for 40 ms.

Figure 11 shows the waveform distribution of cave Model 3 with splay walls whose width is 3 m. In this figure, the intensity of the sound wave is represented in gray scale. The waveform shows that the splayed walls reflect part of the sound wave back to the audience area, which can enhance the sound energy of some parts.

5.2 Results and Analyses

Laterally reflected sound energy is related to sense of space, and the definition of lateral energy factor is

$$LEF = \int_{5ms}^{80ms} p_L^2(t)\,dt \Big/ \int_0^{80ms} p_0^2(t)\,dt \quad (2)$$

Eq. 2 indicates that the ratio of the energy delayed within 5~80 ms after the arrival of direct sound to the total energy arrived within 80 ms. To determine the contribution of splay walls to the early sound energy, for the same receiving point, the effect of early reflection sound before and after the splay walls is added was compared. The early sound energy ratio is defined as

$$R_e = \int_0^{50ms} p_1^2(t)dt \Big/ \int_0^{50ms} p_0^2(t)dt \tag{3}$$

where p_0 represents the sound pressure when there are no splay walls and p_1 represents the sound pressure when there are splay walls. When R_e is greater than 1, it means that the reflected sound energy with splay walls is greater than that without splay walls. Since the difference of *LEF* and R_e of each model obtained after simulation is not large, the results are averaged and listed in Figure 12 and Figure 13.

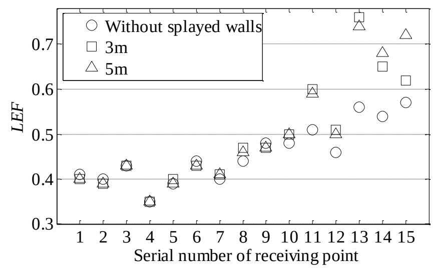


Figure 12 : The average lateral energy factor of all the models

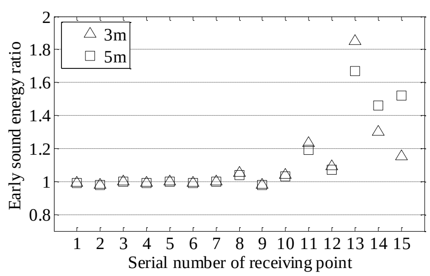


Figure 13 : Early sound energy ratios of all the models

From the two figures, the *LEFs* of these 15 receiving points are within 0.35~0.76, and the early sound energy ratios are within 0.98~1.85. For receiving points 1~7, the *LEF* and early sound energy of these three situations are almost similar, while for receiving points 8~15, the *LEF* and the early sound energy of models with splay walls are larger than those without splay walls, which shows that splay walls can strengthen the lateral reflection of sound on both sides of the auditorium but have little effect on the middle of the auditorium. If the length of the stage is shortened, it can enhance the acoustics of the middle part of the auditorium. Schroeder once noted that classical theater buildings are high and narrow, and boxes and large architectural decorations help to produce more lateral reflection sound, so the sound quality of these classical theaters is better. On the contrary, the modern theater always has a large horizontal span, and it lacks the early lateral reflection of sound, so its sound quality is poor. The same is true for the stage; that is, the horizontal span of the stage is smaller, and if there are splay walls on both sides of the stage, the auditorium can produce more lateral reflection sound, and the listening sense will be better. For receiving point 14 and receiving point 15, the *LEF* and early sound energy of splay walls with a width of 5 m is larger than that with a width of 3 m, which shows that the larger the width of the splayed walls, the greater the sound effect of the larger range of the auditorium. In conclusion, splay walls can not only enlarge the size of the stage and beautify the stage shape but also improve the sound quality of the stage.

6 Conclusion

In this paper, the recursive equations are improved by combining local conformal finite-difference time-domain equations of acoustic waves proposed by predecessors with the perfectly matched layer boundary. The results of objective acoustic parameter analysis of pulse responses and listening tests show that sense of space and reverberation of the stage with a cave are stronger. It is confirmed that the early decay time (EDT) is better than the reverberation time T_{30} to explain the reverberation of the court stage without a roof. Similar to the design concept of modern coupling space, this cave structure can improve the sound quality of the building.

The stages with a backstage of horizontal and longitudinal caves meet the architectural concept of Chinese architecture, and also provide more space for actors and performance equipment storage. There is no doubt that the longitudinal cave opening to the auditorium is designed to provide more and louder sound to the audience. The longitudinal cave-style stage adopted by the acoustical designers in ancient China fits the design concept of modern coupling space, which indicates that the cave-style stage is an earlier acousticcal building in China that adopts the form of coupling space.

In addition, the splay walls on both sides of the stage can enhance the sound energy of some parts of the auditorium, which is similar to the role of the reflector board in the modern stage. To summarize, it can be seen that the ancient people's architectural wisdom was advanced, which inspires us to further explore the technology of ancient Chinese acoustic architecture and apply it to modern stage architecture.

Acknowledgments

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THE ACOUSTICS OF THE HOLY FAMILY CHURCH IN SALERNO

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Résumé

L'église de la Sainte Famille de Salerne (Italie) construite en 1971 a radicalement révolutionné la structure spatiale de la conception des bâtiments préconciliaires. La géométrie circulaire du toit a nécessité un travail complexe avec l'emploi d'ouvriers de chantier naval pour aboutir à une géométrie unique. Cependant, des géométries futuristes telles que celle-ci entrainent des conditions acoustique complexe, comme cela est apparue une fois la construction achevée. Dans cet article, les résultats des mesures de la distribution spatiale des caractéristiques acoustiques dans ce grand espace sont rapportés. L'analyse des valeurs des paramètres acoustiques confirme les mauvaises conditions acoustiques pour l'écoute de la parole et de la musique. A l'aide de la modélisation, les auteurs ont étudié des solutions possibles pour la correction acoustique de cette architecture moderne. Cet article rend compte des conclusions d'une telle étude.

Mots clefs : église, mesures acoustiques, acoustique de culte, diffusion sonore, temps de réverbération

Abstract

The church of the Holy Family in Salerno (Italy) built in 1971 radically revolutionized the spatial structure of pre-conciliar church building design. The circular stepped geometry of the roof required a complex work with the employment of shipyard workers to come out with a unique geometry. However, such futuristic geometry also resulted in challenging conditions for its acoustics, as they emerged when the construction was completed. In this paper, the results of measurements of the spatial distribution of the acoustic characteristics in this large space are reported. The analysis of the acoustic parameter values confirms the poor acoustic conditions for speech and music listening. With the help of modelling, the authors have investigated possible solutions for the acoustic correction of this modern architecture. This paper reports the conclusions of such a study.

Keywords: church, acoustic measurements, worship acoustics, sound diffusion, reverberation time

1 Introduction

Churches are complex acoustic places due to their shape and large size, along with the presence of side chapels, vaults, and domes that represent focusing geometries and coupled volumes [1, 2]. Moreover, the typical use of acoustically reflecting materials such as marbles contributes to the formation of highly reverberant conditions in these large spaces [3, 4]. It is worth noting how the absence of acoustically absorbing materials inside the church leads to several problems such as the increase in reverberation time values with the increase in volume [5, 6]. As well as a significant sound absorption generated by the presence of the congregation in the central area which determines considerable changes in the acoustic conditions as the number of people occupying the pews changes. Thus, often churches that have poor sound characteristics especially when they only partially occupied. The long reverberation that develops in churches enhances listening to the music played on organs, Gregorian chants and different types of the choir. The reverberation, generated by the repeated reflections of the sound waves on the walls, increases the sense of participation of the congregation. Churches are currently used for two different activities, that in some ways are opposing when considered from an acoustic point of view: verbal communication with the congregation, recitation of psalms and prayers, explanations and comments of sacred texts [7]. Usually, all activities require a short reverberation, while the optimal listening of choirs and sacred music requires a long reverberation time. In many churches, there are conditions in which the congregation must pay close attention to understand the spoken word. To remedy these problems, expensive and sound amplification systems are adopted which, if they are not installed properly, can worsen listening and thus worsen the comprehension of speech. During the celebration of liturgy, different types of sound messages coexist, each of which requires different acoustically optimal conditions. Organ music requires an optimal reverberation of about 2 to 3 seconds to encourage a sense of congregation participation; music from musical instruments requires an optimal reverberation of 1.5 seconds. Whereas, sermon readings or the homily require a short sound tail with an optimal reverberation time of about 1.0 seconds to obtain good speech intelligibility. To have acoustics suitable for all the elements of the liturgy, a church should be transformed into a room with variable acoustics. In the Middle Ages, the acoustic correction in some churches was obtained by inserting amphorae in the sidewalls, which exploited the principle of Helmholtz resonators.

Moreover, small stages were sometimes made in the centre of the aisles where the speaker stood and modulated

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his own voice thus being understood by the congregation. Another solution was to create large screens behind the ambos, where the priest stood to give the homily, in order to focus the sound on the congregation. An analysis of the size of church volumes according to the architectural style shows an evolution characterized by a progressive growth of dimensions culminating in the large volumes of the Gothic and Renaissance period, in which the dimensions of the churches had to reflect the political power of the civil communities or nuns who had built them. Today, the size of churches has become smaller, but the use of concrete has led to a worsening of the acoustic conditions. It is useful to mention that the acoustic characteristics are not always the same in the whole area of the considered environment; they depend on the actual shape of the environment. The reverberation is almost independent of the shape as well as the particular position of the receiver, while the clarity and intelligibility of the speech depend on the distance from the sound source to the receiver, its visibility and the possibility of receiving the reflections that reinforce the components of the direct sound.

2 Church Architecture

Located in the neighborhood of Fratte in Salerno, a popular district of the city, the Church of the Holy Family is a significant work of contemporary architecture. Designed in 1968 by the architect Paolo Portoghesi, in partnership with the engineer Vittorio Gigliotti, it was built between 1971 and 1974 [8-10]. The church is one of the first Italian buildings of worship built entirely of reinforced concrete, whose construction required skilled workers, including teams experienced in shipbuilding, given the particular curvature of the structures. The idea was to create a space for listening with the centrality of the altar and where there was no longer a separation between the celebrant and assembly, but a unity of participation. Space was assumed as a symbolic quality of transcendence, represented by six large circles that, connected with each other, represented unity within the Holy Trinity. The six circles came, with a substantial variation, from the church of "*Sant'Ivo alla Sapienza*"; along with the dome that reinterprets the model of the church of Borromini and rests on walls with irregular and jagged surfaces. In the church of Borromini, the starting spatial figure is based on an equilateral triangle and is the result of a geometric scheme in which the six circles intersect with a triangle. While in the church of Salerno the six circles, instead of being combined according to the equilateral triangle, are combined according to a rotation principle that tries to represent growth geometrically. Therefore, continuity and organicity to express in the architecture the processes of the creation of life [9]. Figures 1 shows the plant and the section of the church, while Figure 2 shows an internal view. The building has a very complex circular structure, which can be described organically as the fusion of three giant trees that with their branches full of leaves circumscribe and define a space: a church that wants to renew the Catholic liturgy at its roots, expressing in the form the indications resulting from the Vatican Council. The

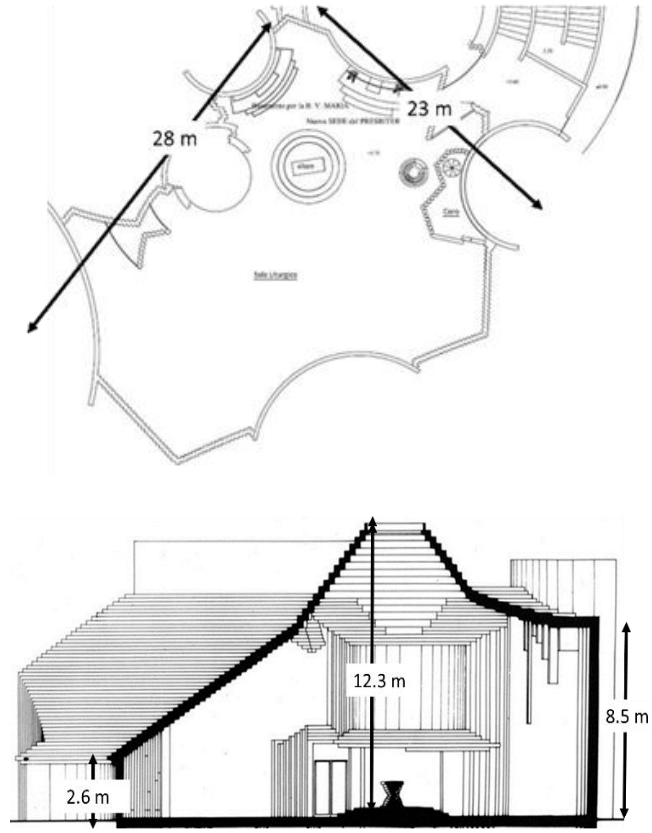

Figure 1: Plant and Section of the church.

Figure 2: Internal view of the church.

Figure 3: Central concave stepped dome.

circle is the inspiring element of the entire work. The church is structurally composed of six centres contained in three concentric circles. The idea was to create a building that expressed, through the choice of curved shapes, the concepts of unity and centrality of the divine. A "sacred" space carefully designed to create an active, full and fruitful of the people of God in the sacred celebration through a liturgical form Christocentric, a central space around the altar, and which opposes the longitudinal spatial forms and shows clerical anti conciliar. Where the altar that acquires a deep meaning strength (located, as the focus of the sacred space – centre not purely geometrical – on three circular steps in marble and an Hourglass concrete base) and where the assembly's attention converges. The ambo is in a decentralized position: it recalls the hourglass style and the material of the altar: the marble pedestal and the concrete structure. The tabernacle is lateral to the altar, in a space adjacent to the sacred hall and clearly visible to the congregation, so as to create, in its silence, the best contemplative atmosphere of adoration and individual prayer. The geometric essentiality of the tubular structures is similar to the burning flames that heat the worshippers and orient them upwards, where the circular openings invite direct contact with God, traditionally imagined in the skies above. The concave steps of the roof of the sacred building, which symbolically evoke the theme of the assembly, exalt the enunciation of another archetypal motif like the amphitheatre [11]. The different colours of the windows symbolize the necessary dialogue between human nature (in the blue-green colour) and the divine nature, in the yellow-white colour. With its stepped roof, with a riser of 0.25 m, derived from the evolution of the concentric irradiance of the spatiality of the six external centres mentioned above (or rather, the spatial fields of the six centres, “enclosed” in geometric circles, expanding in concentric waves, “describe” space in a fluid movement of internal convexities). With the convex vertical extensions of the wall elements, to which the geometric cuts are inscribed for the openings of the coloured windows and with its central concave stepped dome (Figure 3), generated by the crossing of three big vaults above the altar. This convexity of the three times iconography refers to the three divine persons of the Trinity, underlines the great moment of the liturgy: the passion and resurrection of Christ.

3 Acoustic measurements

In order to analyses the acoustic characteristics of the dome, acoustic measurements were carried out using an impulsive sound source located on the altar. The sound source was maintained fixed at 1.5 m from the floor. A BRAHMA digital recorder was used to record the impulse responses in 20 different receivers located in fixed positions and with one source positions, one in the ambo where the homily is officiated.

To reduce any background noise, the measurements were taken without any visitors, so that the impulse responses were recorded under empty conditions. During the acoustic measurements, the background noise was lower than 40 dBA. Figure 4 shows the plan of the church with an indication of position of the sound source on the ambo and the receiver microphone points in the audience area. The recorded impulse responses were elaborated with the Dirac 4.0 software, with several acoustic parameters being analyzed as defined in the ISO 3382-1 [12], such as reverberation time (T30), Early Decay Time (EDT), clarity (C80), definition (D50) and sound transmission index for speech intelligibility (STI) [13]. Figures 5, 6, 7 and 8 show, respectively, the average values and relative standard deviations of the acoustic parameters measured (T30, EDT, C80 and D50), with the sound source on the ambo. The acoustic measurements of the characteristics of the church in its current condition show an excessive length of the reverberation, which is manifested by a reverberation time (T30) with an average value equal to 7 s; an average EDT value equal to 7 s.

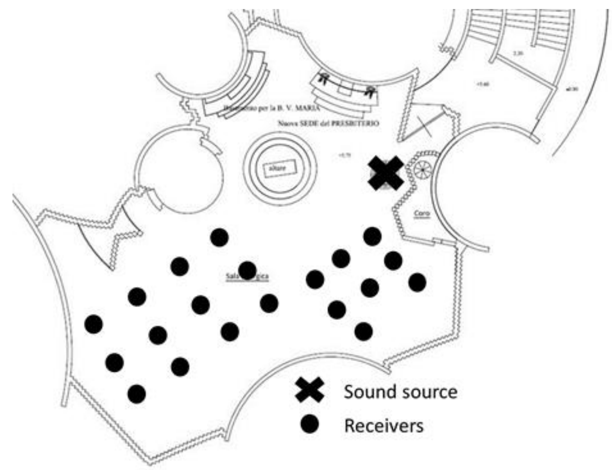

Figure 4: Plan of the church with an indication of the position of the sound source on the ambo and the microphone points in the audience area.

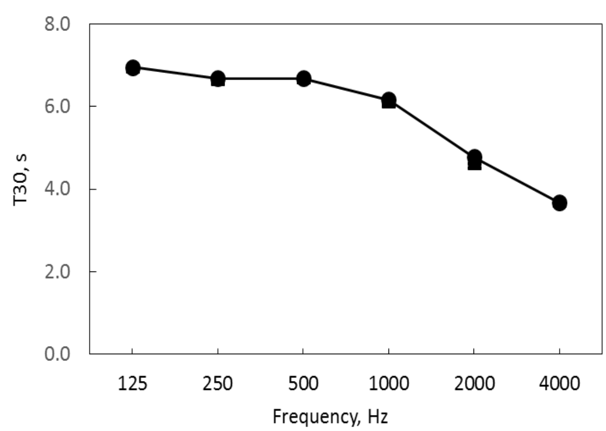

Figure 5: Average measured values of T30 and relative standard deviations.

The clarity average value C80 is equal to -8 dB and the definition average value of D50 is equal to 0.10. The values of the standard deviation for C80 and D50 show substantial differences, due to the fact that the measured acoustic parameters vary significantly from point to point. In this configuration, the acoustic measurements of the characteristics of the church in its current condition show an excessive length of the reverberation. With the sound source on the ambo the reverberation time values T30 and EDT are constant in the frequency range between 125 Hz and 1000 Hz, and thereafter are reduced to 4.0 s at 2000 Hz and 3.0 s at 4000 Hz. Furthermore, the values of the average characteristic acoustic measured when compared with the optimal recommended ones, indicate that in the church, there is not a good speech understanding and listening to musical performances is not satisfactory. To better understand the acoustic characteristic of the church the spatial average distribution of the acoustic parameters in the area where the congregation sits (audience area) were analysed. The values of T30 and C80, as well as the value of the STI (index of speech comprehension), were reported at the frequency of 1000 Hz. Figure 9 shows the spatial distribution of the parameter T30 at the frequency of 1000 Hz, in which it is possible to notice that T30 assumes a value equal to 6.5 s. These values are uniform within the church but are such as to exceed the recommended values for the correct listening of musical performances, as reported in current literature. Figure 10 also shows the spatial distribution of parameter C80 at the frequency of 1000 Hz, in which it is possible to notice that C80 assumes a value equal to -8 dB for points near the sound source, and then decreases to -10 dB for points far from the sound source. These values indicate that musical performances in the church are not perceived in a suitable way because the C80 values are not included in the optimal range reported in the literature.

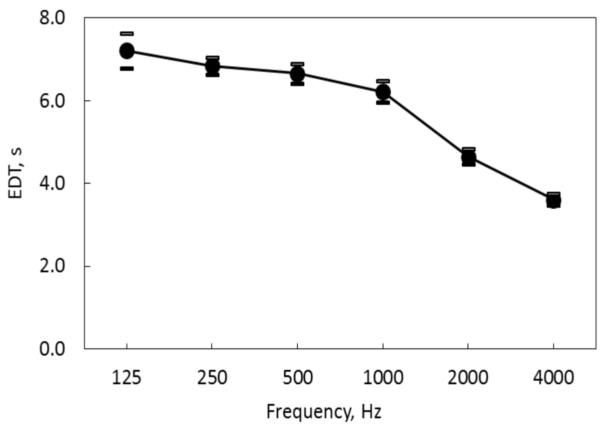

Figure 6: Average measured values of EDT and relative standard deviations.

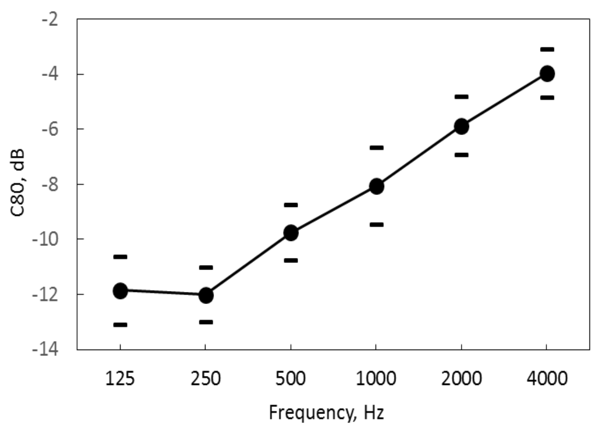

Figure 7: Average measured values of C80 and relative standard deviations

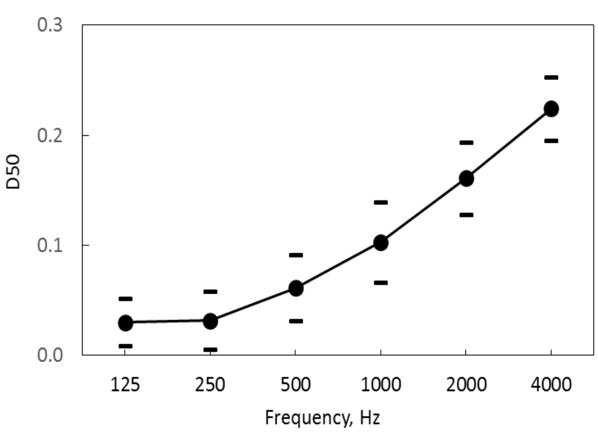

Figure 8: Average measured values of D50 and relative standard deviations

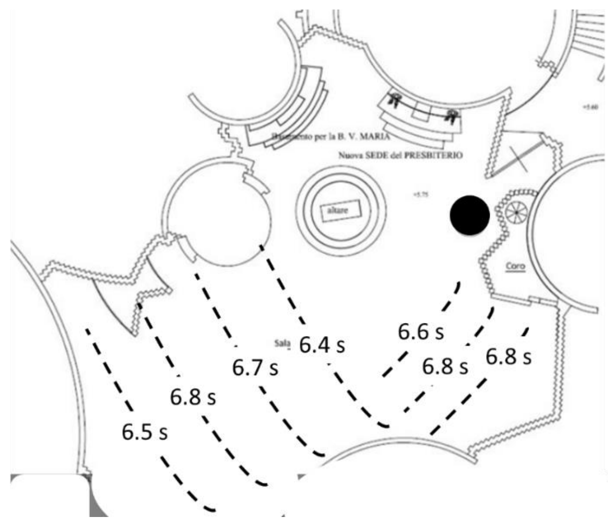

Figure 9: Spatial distribution of parameter T30 at the frequency of 1000 Hz

Figure 11 shows the spatial distribution of the STI parameter, in which it is possible to notice that STI assumes a value equal to 0.3 for the points near the sound source, and then slowly decreases to 0.26 for points far from the sound source. In the area near the ambo where the sound source is located, the value of the STI is equal to 0.38 and then decreases to 0.34. The value of the STI in every point of the church is an indication of the low comprehension of the spoken word. The church in the current state does not meet the criteria of good listening for music and speech.

For the position of the sound source, the reverberation times EDT and T30 measured in the absence of public are high due to the presence of poorly sound-absorbing surfaces. The remarkable articulation of the surfaces of the roof with the stepped section, with the 0.25 m riser, produce diffusive effects for a wide frequency range. Diffusion produces a spatial homogenization of the temporal decay of the sound field that is highlighted by a modest standard deviation of EDT and T30.

Figure 10: Spatial distribution of parameter C80 at the frequency of 1000 Hz

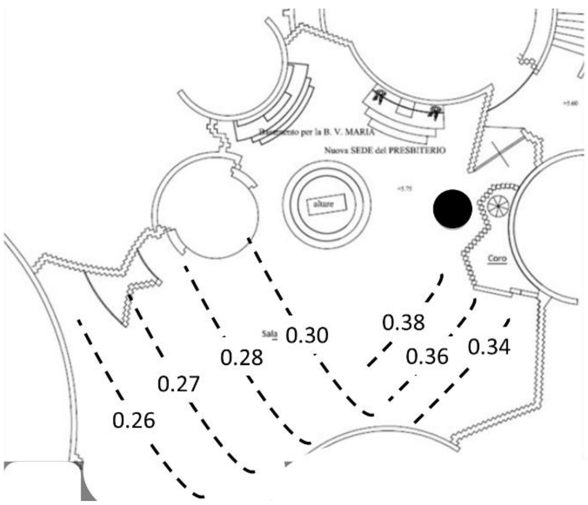

Figure 11: Spatial distribution of parameter STI.

A computer simulations with the software Odeon were carried out to study the effect of sound absorbing systems that can be adopted in the respect of the original architecture of the venue. Odeon uses a hybrid method of images plus ray-tracing. Figure 12 shows the Odeon virtual simulation model of the church. The first step consists in the calibration procedure, it consists in the comparison of measured quantities with analogous calculated ones. If the difference is unsatisfactory, a suitable calibration of the acoustic model is to be carried out in order to reduce the difference to a reasonnably low value. When a virtual model has been obtained which represents adequately the observed state of a room, desired changes or insertions can be considered.

To calibrate the acoustic model, measured averaged values of T30 were compared with the corresponding values calculated with Odeon for each octave band. An iterative procedure was used to reduce the difference between the measured and calculated values of T30. This implied little adjustments of the sound absorption coefficients (α) and the scattering coefficients (s) [14-16]. The interventions for the

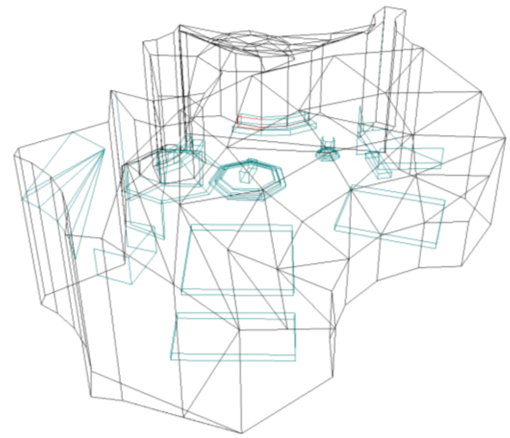

Figure 12: Odeon virtual simulation model of the church.

acoustic correction in the churches subject to constraint can be exclusively of the reversible type and must not alter the existing surface finishes. The structures must be temporary and therefore easy to place and remove to preserve the beauty of the environment, or positioned in particular areas in order not to affect the aesthetics of the structure. In the current configuration inside the church, the measured values of the reverberation time and of the other acoustic parameters are excessive compared to those required for a good understanding of speech. The solutions that allow you to respect the constraints imposed are the insertion on the side windows of transparent micro-perforated sheets (*Barrisol type*) and the insertion of sound-absorbing cushions under the benches. The evaluation of the goodness of the acoustic correction was carried out with the help of the Odeon software for architectural acoustics. Table 1 shows the sound absorption coefficient values of the materials used in the numerical simulation

Table 1: Sound absorption coefficient values of the materials used in the numerical simulation

Frequency, Hz	125	250	500	1 k	2 k	4 k
sheets	0.1	0.2	0.7	0.8	0.6	0.6
cushions	0.4	0.7	0.75	0.8	0.8	0.8

It was hypothesized to cover the side windows with transparent micro-perforated sheets for a surface of 134 m^2 of transparent acoustic sheet. Furthermore, it was decided to intervene on the assembly benches present inside the church as they are complex elements, built in wood and are therefore acoustically reflective elements. The use of benches covered with cushions of sound-absorbing material allows to obtain a good acoustic correction. For these reasons, simulations were carried out by inserting 100 m^2 of sound absorbing material under the benches. The acoustic correction with the insertion of sound-absorbing sheets and sound-absorbing cushions leads to a reduction in the reverberation time, so as to obtain an optimal value for the C80, but not for the D50. Figures 13, 4, 15, and 16 shows the average values of the acoustic characteristics (T30, EDT, C80 and D50) of the church in its current state, with the windows covered with transparent acoustic sheets and with the benches covered with soundproofing cushions.

4 Conclusion

The church presents problems for the understanding of speech due to the large volume and presence of reflective materials. The acoustic measurements with the empty church have provided an average reverberation time (T30) of about 7 s. The church is not suitable for the understanding of speech or listening to musical performances. However, a good speech understanding inside churches has become necessary due to the type of religious service, based on a vocal message after the Vatican II Council. For the church to be used correctly to listen to the speech an appropriate acoustic correction should be carried out inside. Panels of sound-absorbing materials should not be used since they are not suitable for churches, transparent micro-perforated sheets withe absorbent cushions should be used instead. Micro-perforated sheets and cushions under the benches have good acoustic characteristics. The use of the transparent sheet means that the walls of the church are visible and cushions under the benches so the aesthetics values are safeguarded.

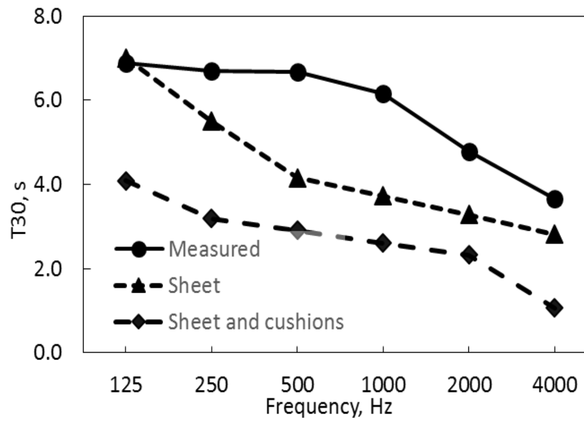

Figure 13: T30 average values.

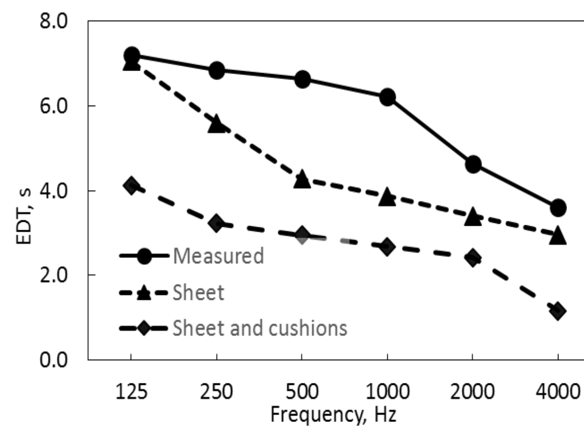

Figure 14: EDT average values

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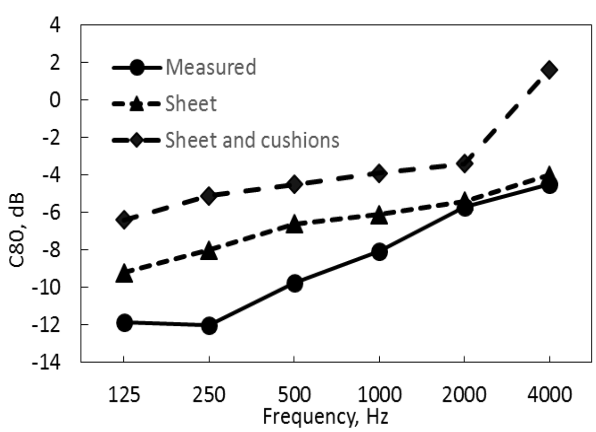

Figure 15: C80 average values

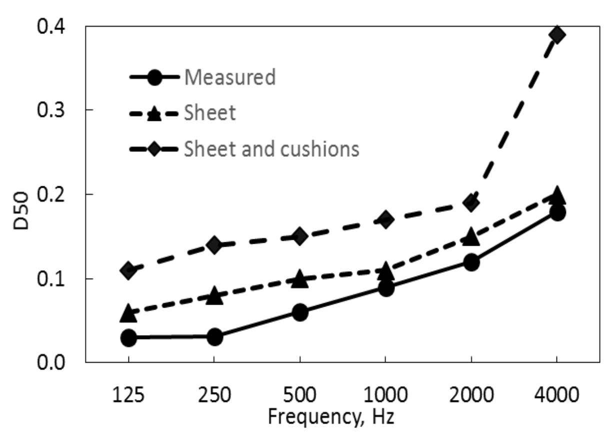

Figure 16: D50 average values

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Real-time Ultrasound-Enhanced Multimodal Imaging of Tongue Using a 3D Printable Stabilizer System: A Deep Learning Approach

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Résumé

Malgré une prise de conscience accrue de l'importance de l'articulation, il reste difficile pour les instructeurs de répondre aux besoins des apprenants en matière de prononciation. Il existe des outils pédagogiques pour l'enseignement et l'apprentissage de la prononciation bien qu'ils soient relativement rares. Récemment, une méthode multimodale améliorée par ultrasons (Enunciate) a été mise au point par des chercheurs de l'Université de Colombie-Britannique (UBC) pour visualiser les mouvements de la langue d'un apprenant, superposés à la face du locuteur. Des vidéos préenregistrées utilisant ce système ont été évaluées pour plusieurs cours de langues via un paradigme d'apprentissage mixte dans plusieurs classes de niveau universitaire. Bien que ce système multimodal ait été utilisé avec succès pour l'apprentissage de la prononciation, il nécessite encore des travaux manuels et des manipulations humaines, ainsi que la nature hors ligne du système, où les utilisateurs ne peuvent pas voir leurs mouvements de langue en temps réel. Dans cet article, nous avons développé un nouveau système d'entraînement à la prononciation multimodal complet, automatique et en temps réel, qui bénéficie de puissantes techniques d'intelligence artificielle, pour répondre aux difficultés des précédentes approches multimodales améliorées par ultrasons telles que le système UBC. Nous avons combiné les avantages de la technologie des ultrasons, de l'impression 3D et des algorithmes dde deep learning pour améliorer les performances des systèmes précédents. Plus précisément, notre système d'entraînement à la prononciation comprend plusieurs modules pour faciliter la personnalisation et le développement futurs par d'autres chercheurs. Il permet aux apprenants d'une langues d'observer automatiquement leurs mouvements de langue sur leur visage, en temps réel et avec une restriction minimale pendant la session de formation linguistique.

Mots clefs: Technologie ultrasons, formation à la prononciation, production de la parole et, visualisation de la langue, deep-learning, extraction automatique de contour, stabilisation de sonde.

Abstract

Despite renewed awareness of articulation importance, it remains a challenge for instructors to handle the pronunciation needs of language learners. There are relatively scarce pedagogical tools for pronunciation teaching and learning. Recently, an ultrasound-enhanced multi-modal method (Enunciate) has been developed by researchers at the University of British Columbia (UBC) for visualizing tongue movements of a language learner overlaid on the face-side of the speaker's head. Pre-recorded videos using that system was evaluated for several language courses via a blended learning paradigm at several university-level classes. Although that multi-modal system successfully utilized for pronunciation training, it still requires manual works and human manipulation as well as offline nature of the system, where users can not see their tongue movements in real-time. In this article, we developed a new comprehensive, automatic, real-time multi-modal pronunciation training system, benefits from powerful artificial intelligence techniques, to address the difficulties of the previous ultrasound enhanced multi-modal approaches such as the UBC system. We combined the advantages of ultrasound technology, three-dimensional printing, and deep learning algorithms to enhance the performance of previous systems. Specifically, our pronunciation training system comprises of several modules for easier future customization and development by other researchers. It empowers language learners to observe their tongue movements automatically, augmented on their face view in real-time with minimal restriction during the language training session.

Keywords: Ultrasound technology, pronunciation training, speech production, tongue visualization, deep-learning, automatic contour extraction, probe stabilization.

1 Introduction and Previous Works

Communication skill is one of the essential aspects of the second language (L2) acquisition so that it is often the first indication of a language learner's linguistic abilities [1, 2]. Pronunciation directly influences many social interaction skills of a speaker, such as communicative proficiency, performance, and self-confidence. Previous studies revealed that other aspects of L2 learning could be developed easier by accurate pronunciation [3, 4]. However, one of the most challenging skills to master in L2 training is to teach the correct pronunciation of tricky words [5] in traditional classroom settings.

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In practice, it is difficult for an L2 learner to utter difficult words or sounds precisely without any visual feedback of a native speaker and lack of awareness of how sounds are being articulated [5], especially in cases where the target sounds are not easily visible [1]. Visual feedback approaches have been developed over the past decades to facilitate L2 students to perceive moving speech articulators during speech or training sessions. These methods benefit from a range of instruments (called Electronic Visual Feedback (EVF)) [6], including ultrasound imaging, electromagnetic articulography (EMA), and electropalatography (EPG) [7]. Amongst those technologies, ultrasound imaging is non-invasive, safe, portable, versatile, user-friendly, widely available, and increasingly affordable. Besides, ultrasound modality offers high dimensional continuous real-time data with acceptable frame-rate.

Furthermore, ultrasound technology is capable of recording and illustrating the whole regions of the tongue (although the mandible sometimes obscures the tongue tip [1]) during both dynamic and static movements. Other imaging modalities such as MRI and X-ray (more specifically cinefluorography) are also capable of showing a mid-sagittal view of the tongue. However, these techniques are often prohibitively expensive, non-accessible, and invasive [8]. New technology-assisted language training methods [5,7,9–15], such as multimodal approaches using ultrasound imaging [1, 16, 17], have been successfully employed for language pronunciation teaching and learning, providing visual feedback of tongue gestures and poses. However, this technology is yet far from commercializing for use in every language education institutes.

In this study, we proposed a fully automatic pronunciation training system enables language learners to see their tongue on their face view in real-time. Our modular system, with a range of capabilities and facilities, provides a comprehensive toolbox for researchers applicable for different fields of linguistics applications from pedagogical to quantitative analysis. The authors observe several gaps in the current ultrasound multimodal approaches for L2 pronunciation training [1, 16–18]. In previous ultrasound-enhanced multimodal systems, manual synchronization between video and audio data, and image enhancement are essential parts [19]. In these systems, for quantitative analysis, one frame should be frozen manually. The whole super-imposing process of ultrasound and the side-face view is manual using editing software. All these manual works are time-consuming, subjective, and error-prone tasks, which require a knowledge of video and audio editing [1, 5, 17]. In our proposed system, manual modification of data is not necessary as well as all the super-imposing procedure are accomplished automatically and in real-time. For any further analytic study, users can work on video data in real-time without stopping the training session. Besides manual works, users can watch only pre-recorded videos, usually created from the pronunciation of native speakers, and users can not compare their tongue gestures with native speakers simultaneously on the same system. Lack of information about the correct position, orientation, and scale of the ultrasound data forces researchers to stabilize the camera and head of users during video recording [1, 16, 17], without any flexibility for the user's head position, which makes language training non-conformable for the user. Therefore, these systems can not utilize in classrooms with many L2 students in real-time. For pedagogical applications, the position of an ultrasound probe is not crucial. However, for quantitative linguistic analysis, the ultrasound probe also should be fixed during video recording in the mid-sagittal plane. To alleviate these difficulties, we designed a simple stabilizer, including tracking markers called UltraChin. Using UltraChin and our deep learning tracking method, there is no need for fixing head movements. Therefore, users can observe their tongue gestures in real-time instead of watching pre-recorded videos.

1.1 Ultrasound Tongue Imaging

Nearly 50 years ago, one-dimensional ultrasound was first used effectively for illustration of one point at a time on the tongue's surface [20]. The two-dimensional ultrasound (B-mode settings for mid-sagittal or coronal view) has been employed in speech research since 40 years ago [21]. Nevertheless, due to the recent development of ultrasound imaging technology with greater image quality and affordability, it became an essential tool for imagining the articulators in speech research and pedagogical applications [1, 14].

Ultra-high frequency sound, both emitted and received by piezoelectric crystals of ultrasound transducer/probe, creates echo patterns that are decoded as an ultrasound image. Ultrasound signals penetrate and traverse linearly through materials with uniform density but reflect from dense substances such as bone. With the ultrasound transducer held under the jaw and with the crystal array lying in the mid-sagittal plane of the head, the ultrasound screen displays information about the superior surface of the tongue from the root to near the tip [22] (see Figure 1). Procedures and techniques of ultrasound image reconstruction and acquisition, specifically for tongue imaging, have been comprehensively described in [23].

Real-time tracking of tongue gestures and interpretation of ultrasound data by non-expert L2 learners is not always an easy task (see Figure 2 as an example of tongue contour in ultrasound device). Due to the noisy and low contrast images of ultrasound imaging, the tongue surface can be highlighted automatically in real-time for L2 learners, results in easier tracking of the tongue gestures (see the red curve in Figure 1).

One distinct linguistically valuable property of ultrasound imaging is the capability of simultaneous visualization of the front and back of the tongue [14]. Ultrasound has been utilized effectively in L2 pronunciation training [9]. For example, the efficacy of using ultrasound imaging on the pronunciation of North American /r/ and /l/ phonemes has been proven by depicting the complexity of the tongue's shape for L2 language learners [14, 24].

1.2 Ultrasound-enhanced Multimodal Approach

Recently, ultrasound-enhanced multimodal approaches have been applied for supporting L2 pronunciation students in

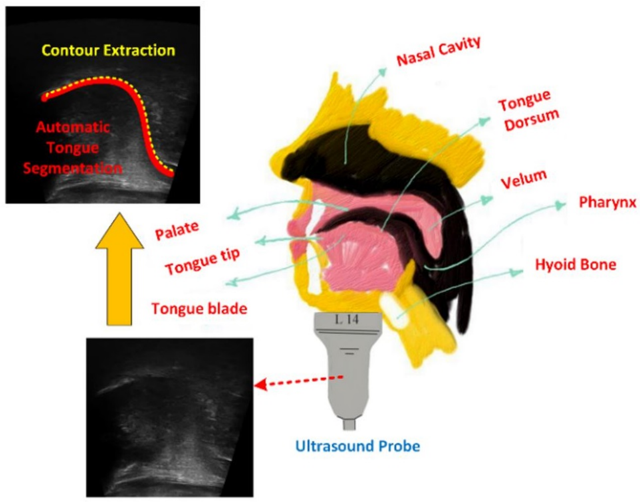

Figure 1: Tongue contour can be highlighted for better understanding of the tongue gestures in real-time video frames.

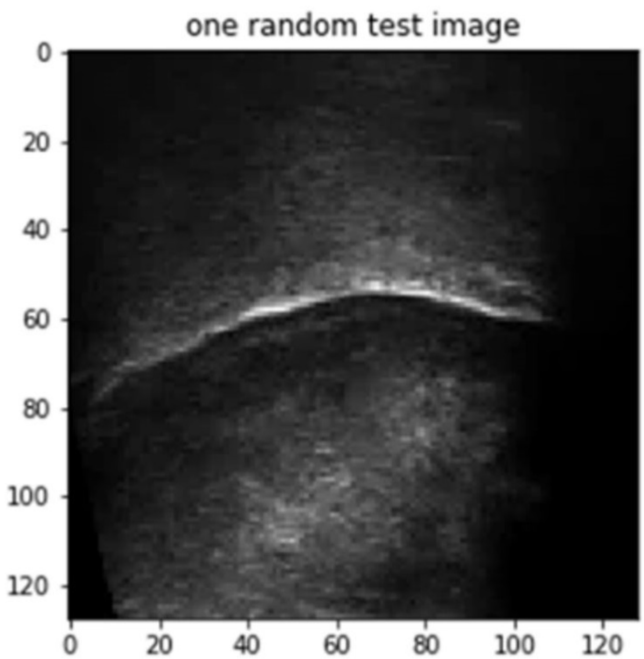

Figure 2: One sample of ultrasound video frame after cropping into a square sized format.

understanding and perceiving the location of their tongue from ultrasound video frames. Significant pioneer investigations of this method have been accomplished by researchers in the linguistics department at the University of British Columbia (UBC) (name of their system is eNunciate) [1, 5, 9, 14, 16, 17, 25]. The key technological innovation of this method is the use of mid-sagittal ultrasound video frames of the tongue, manually overlaid on the external profile views of a speaker's head. This approach allows L2 learners to observe pre-recorded videos comprising speech articulation of a native speaker superimposed on face profile [5,9,16]. In order to highlight the whole tongue region in recorded ultrasound video frames, the intensity of pixels related to the tongue region was changed manually to pink color [9, 16].

Benefits of a multimodal method for pronunciation language training have recently been investigated in a few studies [7, 18, 26]. However, manual work is yet extensive in many steps of these methods (pre-processing such as image enhancement, during the exam like overlaying ultrasound frames on RGB video frames, and post-processing including highlighting of the tongue region and audio/video synchronization). Besides, the overlaid videos come with some non-accuracy due to the lack of transformational specification (exact scale, orientation, and position information) of the ultrasound frame for superimposing on the face view.

In techniques such as eNunciate [16, 25] accurate transformation information cannot be generalized for real-time superimposing ultrasound data on face view. For this reason, the user's head should be restricted to one position during recording using stabilizers. Accurate synchronization between ultrasound data, video frames, and acoustic records is another challenge for those previous studies [19, 27]. A quantitative study of tongue movement only viable after freezing a target frame or during post-processing of recorded frames [5, 11]. Besides all these difficulties, language learners can only watch pre-recorded videos. In this study, we proposed a

Figure 3: L2 learners can see their tongue gestures during a pronunciation training session using an ultrasound-enhanced multimodal approach. Real-time perceiving the tongue location in the mouth is significantly easier and more effective than looking at multimodal pre-recorded videos.

new system that enables users to observe their tongue movement in real-time on their face view without any considerable restrictions. Our ultrasound-enhanced multimodal system benefits from state-of-the-art deep learning techniques to calculate transformations required for real-time superimposing ultrasound data on face view. Figure 3 illustrates one frame captured using our ultrasound-enhanced multimodal technique.

1.3 Artificial Intelligence for Second Language

Artificial intelligence (AI) is a branch of computer science when machines execute tasks that typically require human intelligence [28]. Machine learning is a subset of AI, where machines learn skills by experiencing and acquiring knowledge without human involvement. Inspired by the functionality of the human brain, artificial neural networks are trained using a large amount of data to perform a task repeatedly. Deep learning algorithms are artificial neural networks with many (deep) layers similar to human brain structure [29]. Deep learning-based methods and applications in the image processing field such as object detection [30, 31] and image segmentation [32] have been a research hotspot in recent years. Deep learning methods are robust in automatic learning of a new task. In contrast, unlike traditional image processing methods, they are capable of dealing with many challenges such as object occlusion, transformation variant, and background artifacts [31–33].

The tongue surface is the gradient from white to the black area at the lower edge [23] in the form of a thick, white, and bright curve in ultrasound data. Although the tongue contour region can be viewed in ultrasound data, there are no hard structure references. For this reason, it is a challenging task for non-expert users to locate the tongue position and interpret its gestures without any exercise [16, 23]. Furthermore, due to the noisy and low-contrast images of ultrasound technology, it is an even more laborious task for users to follow the tongue surface movements, especially in real-time applications [16]. Instead of using a guideline on the screen (usually adopting the palate [11]), employing an automatic tracking technique, a language learner can perceive the real-time location of the tongue respect to landmarks of the face.

The rest of this article is structured as follows. Section 2 describes our proposed automatic and real-time ultrasound-enhanced multimodal pronunciation system. In this section, we explained each module of our system separately in detail to address each problem of previous systems mentioned before. Section 3 summarizes our experimental results. Finally, section 4 discusses and concludes our paper as well as potential future directions.

2 Methodology

2.1 UltraChin for Stabilization and Tracking

In previous ultrasound-enhanced multimodal studies, the head of language learners should be stabilized during video and ultrasound data collection as well as it is necessary for accurate superimposing video frames [1, 5]. A consequence of this restriction is a considerable reduction of the user's head flexibility. Moreover, the language learner should concentrate on the user interface for a long time with those limited movements where it might result in body fatigue and eye strain, ultimately reducing the effectiveness of the L2 training session (see Figure 4 for some samples of ultrasound probe stabilization methods). In a recent study by [18, 26], researchers could alleviate this difficulty by tracking of the face profile automatically. Tracking information made it easier for researchers to overlay video frames manually. However, tracking of the face is a subjective idea with low accuracy due to the variant of face angles and characteristics. It is noteworthy to mention that stabilizing the ultrasound probe is not necessary for pedagogical applications.

(a) (b) (c) (d)

Figure 4: An illustration of some stabilization methods for head and probe. Designed helmets keep the probe under the chin, a) [34] b) [35]. One helmet which is fixed to the wall [36], and d) Optical tracking system for the head alignment [22].

In our system, users can keep the probe under the chin without any extra pieces of equipment (we named this state of our system as freehand). However, our goal is to provide facilities for all aspects of speech research, including pedagogical, both qualitative and quantitative analysis. For this reason, the freehand method can not guarantee that the probe orientation is always in the mid-sagittal plane during articulation. In order to make our system independent from the user's face profile and video frame superimposing process more accurate, we designed UltraChin, which is a universal 3D printable device compatible with any ultrasound probes. In general, UltraChin is used for two reasons in our proposed system : I) As a reference marker for probe tracking module, II) for keeping the probe under the chin aligned with the mid-sagittal plane of language learner's head.

In order to overlay the ultrasound video frame on a user's face automatically, for each frame, three transformation parameters related to the probe location should be calculated for each frame in real-time, and UltraChin markers provide locational information for this calculation. Other types of tracking markers as a reference have been employed in few studies for the head, palate, and tongue alignment correction purposes [37, 38]. UltraChin was created after several generations of designing (using SolidWorks software), 3D printing (using MakerBot Replicator 2), and testing on language learners (see figure 5 for several generations of UltraChin). In the last generation (see figure 6), we used natural materials in the process of 3D printing for skin sensibility prevention due to the contact of human skin with plastic, which was not considered in previous similar devices [34, 39]. Furthermore, UltraChin is expandable easily by adding extra parts where users can attach other types of sensors, such as electromagnetic tracking sensors. Unlike the previous helmets and stabilizer devices [34, 39, 40] for ultrasound tongue imaging, UltraChin is fully printable without the requirement of extra components such as rubber bands as well as publicly available [1]. One unique characteristic of UltraChin is that the ultrasound

1. https ://github.com/HamedMozaffari/UltraChinDesigns

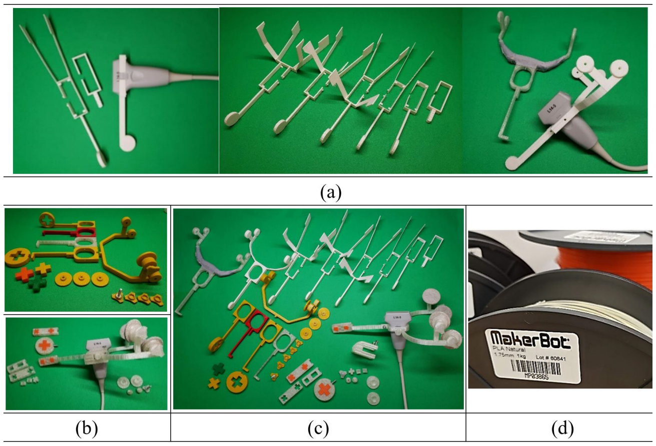

Figure 5: UltraChin : a) Integrated designs, b) Modular designs, c) Different versions and parts, d) Natural PLA materials for printing.

Figure 6: The last generation of UltraChin comprises of several modules. This version is universal and usable for different ultrasound probes as well as capable of being attached to other sensors.

probe is held by the user, which makes the process of data acquisition more comfortable and even more accurate after practicing the user to keep the probe precisely. At the same time, the optimized pressure of the probe on the chin is set by the user after a short training session, results in better image quality and less slippage of the probe and more comfortable sound articulation.

2.2 Automatic Tracking of Ultrasound Probe for Overlaying Videos

In our ultrasound-enhanced pronunciation training system, two video data are recording in real-time from the tongue using an ultrasound device and the face using a webcam camera. Scale and orientation of ultrasound video frames are almost identical because the ultrasound settings are fixed, and the probe is steady under the jaw. However, the user can move her/his head up, down, near, and farther from the webcam camera. For this reason, to project ultrasound frames on the face, we need to transform the ultrasound data on the dynamically changing face view of the user. Because users move in the same plane relative to the camera, having the position of two markers on UltraChin (three degrees of freedom DOFs) can be used to automatically calculate real-time location, scale, and orientation of ultrasound data on user's face in real-time.
Object localization (and detection) techniques determine where objects are located in a given image using bounding boxes encompass the targets. Various deep learning methods have been proposed for object localization in recent years [31, 41]. Similar to facial landmark detection [42], when several key features of the human face are detected as landmarks, we defined two key points on UltraChin extension leg as markers for the sake of probe tracking. Two landmarks (key points) are two upper-left corners of orange squares (see two embedded orange cubes in figure 6). The two markers are tracked automatically in real-time using our new deep convolutional neural network (named ProbeNet). In this method, positions of the two key points on UltraChin provide us transformational information in each frame, comprises of probe orientation, location, and a reference for scaling of the ultrasound data. We designed ProbeNet specifically for the probe tracking problem by inspiring from VGG16 network architecture [43].
Tracking of an ultrasound probe has already been accomplished using different kinds of devices such as electromagnetic, optical, mechanical sensors, and global positioning system (GPS) [44]. However, the primary motivation of those studies is to track the probe in three-dimensional space (usually with 6 degrees of freedom (DOF)). In this study, we considered a simplifying assumption : *ultrasound probe and language learner's face are aligned respect to the camera lens, both in two-dimensional planes* (see Figure 3 where ultrasound frame, segmented tongue dorsum with white color, and two orange markers are aligned respect to the camera lens). Under this assumption, tracking of the probe only requires the calculation of the location in a two-dimensional plane instead of three-dimensional space. For this reason, we selected two key points on the UltraChin, and the tracking problem was converted from three-dimensional space to two-dimensional space.
Figure 7 illustrates the detailed architecture of the ProbeNet for marker detection and tracking. Following advanced versions of VGG network architecture [43, 45], ProbeNet comprises of several standard convolutional layers followed by ReLU activation function and batch-normalization for more efficient network training. In the last block, we used a dense layer with four neurons, which provides 2D positions of the upper-left side of the two markers as well as a drop-out of 50 percent for better generalization over our annotated dataset. During a pronunciation training session, positional information of the two markers are predicted by ProbeNet. These data are used to find the best position, orientation, and scaling of the ultrasound frame overlaying on the language learner's face. Besides a specific calibration procedure is required to convert positional information into orientation and scaling data in the visualization module.

For calibration, we considered a ratio of the distance between the two markers and the width of the ultrasound probe head for scaling of the current ultrasound frame. Triangular geometric considerations between the two markers provide ultrasound frame translation and orientation information over the user's face. It is noteworthy to mention that all procedures of calibration and super-imposing of transformed ultrasound frames on face view are fully automatic and in real-time.

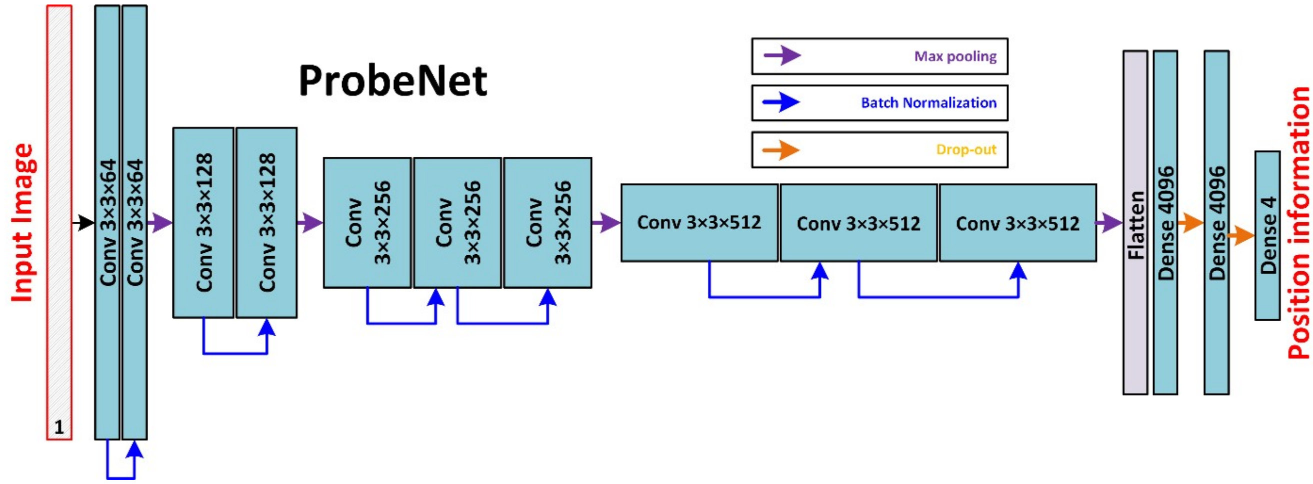

Figure 7: ProbeNet architecture for tracking landmarks on the UltraChin. Output layer provides two sets of numbers as vertical and horizontal positions of each landmark.

2.3 Automatic Tongue Contour Tracking

Typically, during tongue data acquisition, ultrasound probe beneath the user's chin images tongue surface in mid-sagittal or coronal view [46] in real-time. Mid-sagittal view of the tongue in ultrasound data is usually adapted instead of a coronal view for illustration of tongue region, as it displays relative backness, height, and the slope of various areas of the tongue. Tongue dorsum can be seen in this view as a thick, long, bright, and continuous region due to the tissue-air reflection of ultrasound signal by the air around the tongue (see Figure 2). Although the Mid-sagittal view of the tongue in ultrasound alone (e.g., see devices of Articulate Instruments Co.) helps the trend of L2 pronunciation learning, projects such as eNunciate [47] indicate that a multimodal ultrasound-enhanced system is more effective for interactive lingual articulation feedback [17].

The proposed manual coloring of the tongue region with pink color is not applicable for automatic and real-time applications in previous ultrasound-enhanced multimodal studies [17]. In this work, we utilized the most recent fully-automatic and real-time image segmentation method in this literature using deep learning techniques called BowNet [48, 49]. BowNet is used to track the surface of the tongue in video frames (as a continuous highlighted thick region). We used the tongue surface instead of the whole tongue region to facilitate the linguistics researcher for both qualitative and quantitative speech investigations. A detailed description of the BowNet architecture is beyond the scope of the present paper, and we described only several critical aspects of that model briefly for the sake of presentation. Curious readers can refer to studies by [49, 50].

Benefiting from different deep learning tools, including dilated convolutional layers and skip connections, the BowNet model could reach to higher accuracy with a robust performance in the problem of ultrasound tongue contour tracking and extraction in comparison to similar methods [51]. At the same time, there is no compromising for other aspects of the BowNet model like computational cost, the number of trainable parameters, or real-time performance [49]. Figure 8 presents the network structure and structural connections between different layers of the BowNet model [49]. As can be seen from the figure, there is a collaboration between two parallel encoding-decoding networks in BowNet structure. In one path, dilated convolution provides an efficient receptive field while on the other path, deconvolutional layers reconstruct features from the results of the encoder block. The concatenation of both paths provides more flexibility for the BowNet network to train on the search space with better exploration and exploitation ability. Although the BowNet model has few learnable parameters, it performs similar to bigger network models such as U-net [49, 52–54].

Automatic enhancement of ultrasound frames by highlighting the tongue dorsum region (using segmentation technique) enables language learners to focus on managing the challenges of L2 pronunciation learning instead of the interpretation of ultrasound data in real-time. Besides, extracted tongue contours provide teachers and language researchers valuable information for quantitatively comparison studies. It is noteworthy to mention that tongue contour extraction is done after tongue region segmentation using an image processing technique such as skeletonizing or just keeping the top pixels of the tongue region [18, 26, 55]. For a sample of an ideal segmented tongue surface region and extracted tongue contour, see red and yellow curves in Figure 1, respectively.

2.4 Automatic and Real-time Pronunciation Training System

We deployed our pronunciation training system using Python programming language and several standard public libraries as a modular system to enable other researchers to improve or customize each module for any future research. Figure 9 represents a schematic of all modules and their connections, implemented in our pronunciation training system. As can be seen in the figure, there are two streams of data recording in our system, an off-line module that is used for recording videos by native speakers for teaching and an online module

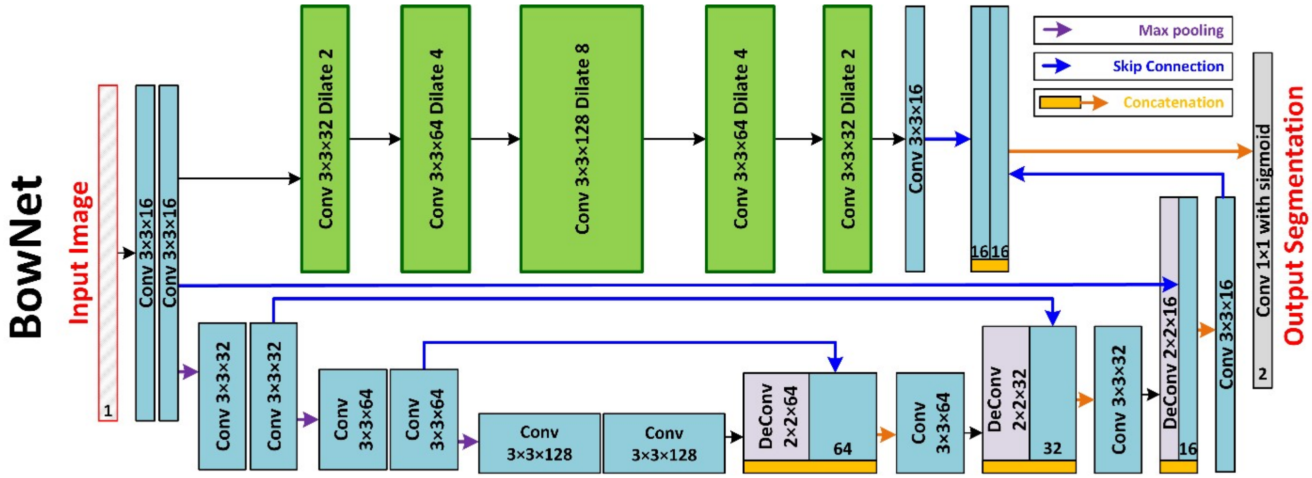

Figure 8: BowNet network architecture for tongue contour extraction automatically and in real-time [48]

for L2 learners, which is used for pronunciation training in real-time.

Ultrasound data acquisition and analysis generally involves capturing both acoustic and ultrasound video frames together so that the audio track can help with identifying target sounds on the ultrasound video stream. Synchronization of those two data can be done during recording or can be part of the post-processing steps, which is an integral and challenging part of having an accurate analysis. Our multimodal ultrasound-enhanced system encompasses different data and techniques during its performance, including tracking of UltraChin's markers, ultrasound data stream visualization, tongue surface segmentation, tongue contour extraction, audio recording and playback, calibration and superimposing video frames, learner's lips visualization (front side), and network connections between ultrasound and workstation. In order to have an approximately synced system, all these stages work together as the following procedure (see Figure 9 for more details) :

1. Face View Recording Module (FVRM) : The data stream from a high-definition webcam camera (Video and Audio) is captured and visualized in real-time. We used a Logitech Webcam with a framerate of 30 fps connected to our workstation (a personal computer with a CPU of 7 cores and 16 GB of memory equipped with a GPU of NVidia GTX1080). Video and audio are already synced in this stage.

2. Ultrasound Data Acquisition Module (UDAM) : Ultrasound stream video data is acquired and sent to the same workstation using Microsoft Windows remote desktop software (freely available on Windows desktops). We employed a linear ultrasound transducer L14-38 connected to an Ultrasonix Tablet with settings of the tongue (depth of 7 cm, a frame rate of 30 fps [23]). It is noteworthy to mention that our ultrasound probe is inadequate for most speech applications, and we only use that ultrasound probe for a demonstration of our system performance. It is noteworthy to explain that instead of working on the ultrasound stream in our Python codes, we used a Windows capturing library to grab ultrasound video from remote desktop software. This method enabled our system to be an ultrasound device-independent where it can work with different ultrasound devices. The price of the ultrasound streaming license for our machine was around $10K in 2018, asked from Ultrasonix company. Our system can capture data for free from all ultrasound machines with a network output port.

3. Ultrasound Probe Tracking Module (UPTM) : The current RGB video frame is fed to our probe tracking module. The pre-trained ProbeNet network model provides locations of two markers on the UltraChin (see the green dot (first marker) in Figure 9 and the connected red line, the middle image between two markers). In a predefined automatic calibration process, position, orientation, and probe head length are determined, and then they are sent to the visualization module.

4. Ultrasound Tongue Contour Tracking Module (UTCM) : Simultaneously with the ProbeNet model, the current ultrasound video frame is cropped, scaled, and fed to the BowNet model for the sake of tongue region segmentation. In this work, we illustrated segmented regions in white color without any post-processing enhancement.

5. Results of three modules UDAM, UTCM, and FVRM, which are three video frames, including cropped ultrasound frame, segmented tongue region, and RGB video frame, are superimposed using calculated transformation information (calibration data) from UPTM. A superimposed video stream is made by weighting the transparency of three video frame data. The result is sent to the visualization module for illustration and recording.

6. Visualization Module (VM) : In this module, a

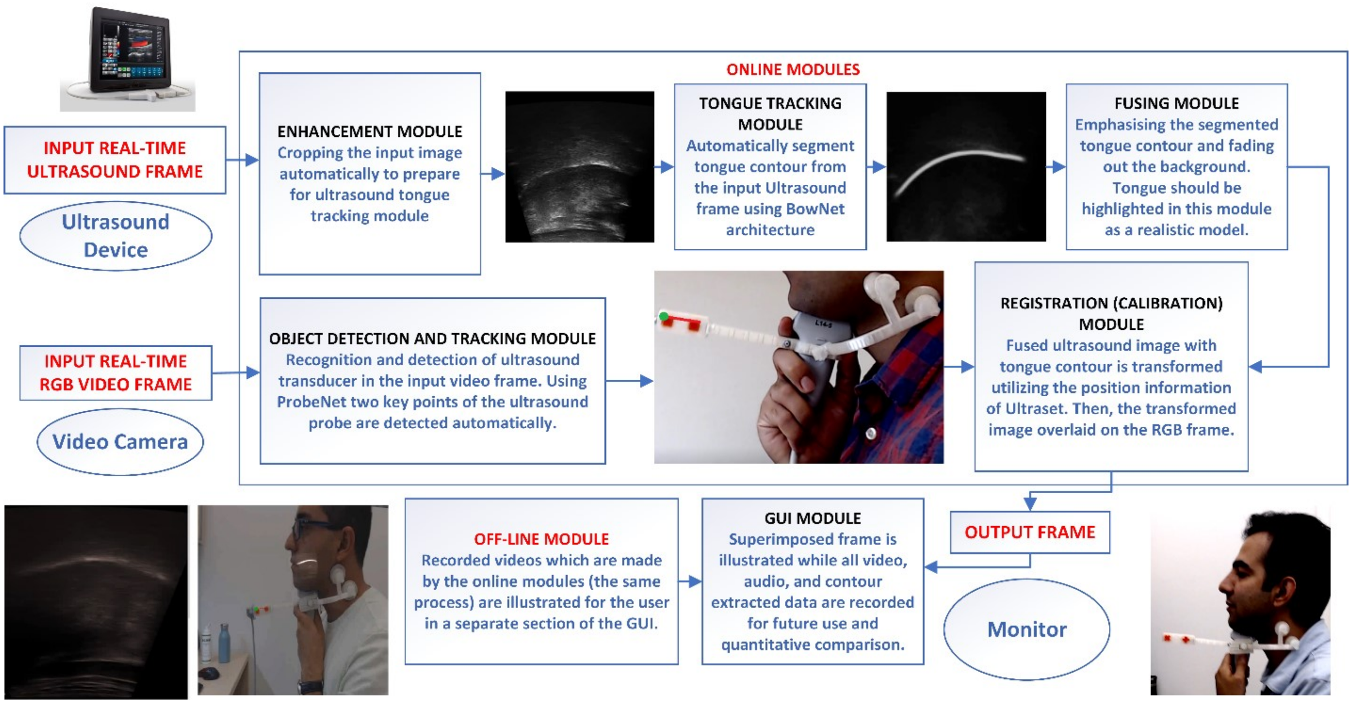

Figure 9: The detailed architecture of our multimodal, real-time, and automatic ultrasound-enhanced pronunciation training system comprises of two main online and offline modules.

simple designed graphical user interface (GUI) in Python language would illustrate several video streams including pre-recorded videos, superimposed video, individual frames from ultrasound and webcam (FVRM and UDAM with video and audio), and results of real-time quantitative analysis. This module is capable of showing data from different ultrasound machines simultaneously. There is also another camera for recording lip movements in front-view during a pronunciation training session. The development of this module is still in the early stages, and we show several windows side-by-side for the user and analytic data in the terminal window. Using two ultrasound devices, future GUI will provide an interactive panel between L2 learner and teacher as well as several comparison data between their tongue contours in real-time.

In our current system, a pronunciation learner or teacher can see several Windows in real-time separately on a display screen at the same time depends on the session target. For instance, as a speech investigation session, a researcher can see weighted ultrasound data superimposed on the face side in real-time, as well as separate non-overlaid ultrasound and RGB videos, accompany ultrasound tongue segmentation results. Having access to data from different modules of our system will assist researchers in comparing ultrasound tongue data qualitatively and quantitatively. Real-time data can be matched with recorded videos from native speaker pronunciation for evaluation of L2 learner's training progress. Moreover, real-time multimodal data could be compared with the data recorded in previous examination sessions as a follow-up study in the diagnosis of speech disorder, as a developed version of our current devices (refer to [56, 57]).

Due to the independence characteristic of our system, respect to the number of image processing streams as a multimodal system, in a different scenario, using two ultrasound devices, L2 language teachers and learners can see and compare their tongues in real-time. Moreover, our system is capable of illustrating the difference between their tongue contours automatically. Due to the lack of the second ultrasound, we can use recorded videos as the second reference video for our comparison studies and for capturing critical moments in the articulation. It is noteworthy to mention that we tested different ultrasound video data recorded by a curved ultrasound probe. The results of the UTCM module were even better in those videos (refer to our last UTCM module [58]). We also tested other webcams with different resolutions for the FVRM module. Results show that lower resolution webcams provide faster tracking but with lower accuracy.

3 Experiments and Results

In this study, we proposed a multimodal ultrasound-enhanced system with several modules, utilizing two different deep learning models. In this section, we explain the preliminary evaluation results of our system focus more on performance illustration of ProbNet, BowNet, and UltraChin. A comprehensive linguistic assessment is required for the evaluation of our system performance in terms of linguistics efficiency. In this section, we only report our pilot pedagogical evaluation from one user.

3.1 Ultrasound Probe Tracking Module

In order to train ProbeNet for tracking the markers on the UltraChin, we created a dataset comprises of 600 images of 3 different participants. Participants use our system for two minutes while a video is recorded from their UltraChin and face view. The recorded frames were annotated manually by placing two pre-defined key points on the upper-left side of orange markers on each frame. Dataset was divided into 80% training, 10% validation, and 10% testing sets. Finally, using our data augmentation toolbox (applying rotation, scaling, translation, and channel shift for images and the two key points), we created a dataset of 5000 images and their corresponding annotation information.

Adam optimization algorithm, with the first and second momentum of 0.9 and 0.999, respectively, was employed to optimize Mean Absolute Error (MAE) loss function [59] during training and validation. A variable learning rate with an exponential decay rate and an initial value of 0.001 was chosen for the training of the ProbeNet. We trained the ProbeNet model for ten epochs (each with 1000 iterations) with mini-batches of 10 images. Our experimental results revealed the strength and robustness of the ProbeNet in the landmark tracking task on the UltraChin device. We got an average MAE of 0.027 $\pm$ 0.0063 for ten times running of the ProbeNet on the test dataset.

3.2 Tongue Contour Extraction

Few previous studies have used deep learning methods for tongue contour extraction with acceptable results [51,52]. For the ultrasound contour tracking module (UTCM), we used one of the recent deep learning models in ultrasound tongue literature called BowNet [49]. Figure 8 represents the detailed architecture of the BowNet. For training settings of the BowNet, we followed the procedure in [49]. Similar to the ProbeNet, for the training of the BowNet model, we separated the dataset (identical to [49]) into 80% training, 10% validation, and 10% test sets.

The BowNet model was trained and validated using online augmentation, and then it was tested separately on the test dataset. Figure 10 presents a sample result of the BowNet model. Due to the more generalization ability of the BowNet network, it provides instances from different ultrasound machines with less false predictions. For more details about the performance evaluation of the BowNet, refer to the original study [49].

The BowNet model was trained to work on data recorded from two ultrasound datasets. The tongue contour tracking performance of our system might be dropped for new ultrasound data. A recent study in ultrasound tongue contour tracking literature [50] has investigated the usage of domain adaptation for several different ultrasound datasets, which can alleviate this difficulty significantly.

3.3 Accuracy Assessment of the UltraChin

Head and probe stabilization is not necessary if the system is only utilized as a pronunciation bio-feedback [60]. However, the accuracy of our system could be improved by adding 3D printable extensions to the UltraChin for head stabilization for a particular linguistic study. However, the main reason for using UltraChin is to track the two markers for the super-imposing of video frames. At the same time, UltraChin provides stabilization for ultrasound probe orientation. In order to evaluate our 3D printable design, we followed the method in [39]. We attached one magnetic tracking sensors, PATRIOT Polhemus Company (see Figure 11 and 12), on the UltraChin and participant's chin in two separate experiments. Six degrees of freedom (see Figure 12) were recorded after ten times repeating a similar experiment. For this experiment, the participant's head was fixed using the method in [36]. We asked the participant to repeat "ho-mo-Maggie" [39] and to open mouth to the maximum position for ten times. We calculated deviations of the UltraChin in terms of transnational (in millimeters) and rotational (in degree) slippages.

Table 1 shows the maximum error of the UltraChin after 10 times experiment. For a better understanding of the UltraChin performance, we checked two different settings where four screws of the device were loose (most comfort) or tight (dis-comfort).

Our experimental results showed that in the case of tightly firming four screws of UltraChin user's chin has a better long term translational and rotational unwanted slippage without losing a significant comfortability for the user's neck. Slippage errors might be even more due to the usage of cushions, skin deformations, and how the participant is keeping the probe under the chin. In compare to the system in [39], UltraChin has more long-term slippage in almost all directions. One reason is that UltraChin has fewer stabilizer arms than previous helmets. Nevertheless, UltraChin errors still are within acceptable deviation limits reported in [39].

3.4 A Preliminary Linguistic Evaluation of Our System

The positional information from real-time output instances of ProbeNet is used to calculate an estimation of the position, orientation, and scale of ultrasound frames on RGB video frames. In this way, real-time segmented tongue contours from ultrasound frames are predicted by the BowNet model and transferred on the face-side of language learners on RGB video frames. Therefore, the language learner can see real-time video frames created by superimposing raw RGB frames, transformed ultrasound images, and tongue segmented images. To illustrate the superimposed image, we considered different weights for the transparency of each image. Figure 13 shows several superimposed samples from our real-time multimodal ultrasound-enhanced system. In the figure, we considered transparency weights as 0.9 for RGB image, 0.4 for Ultrasound image, and 1 for the predicted map, respectively.

For the sake of representation, we also showed a guideline on the UltraChin to help language learners to keep the probe in a correct position in two-dimensional space (see red lines in Figure 13 between two orange markers). During the trai-

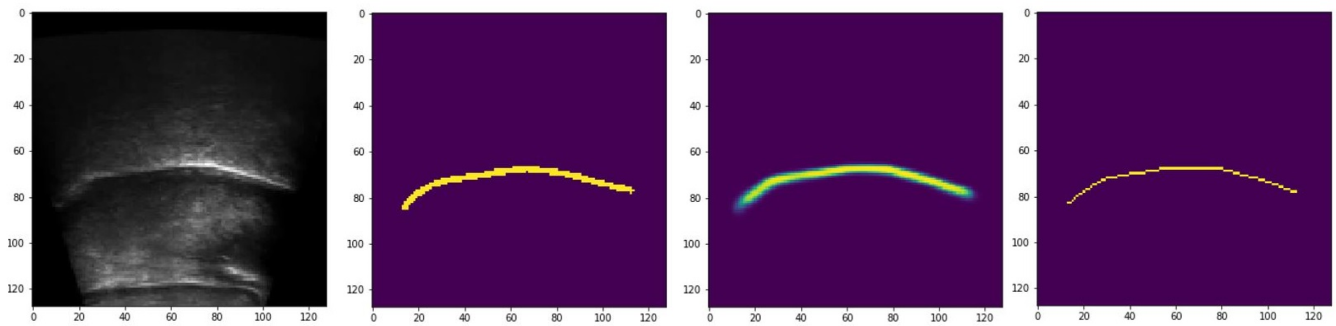

Figure 10: One test sample used for testing the BowNet network. From left to right columns are ultrasound image, ground truth image, predicted map, extracted contour from the predicted map.

Figure 11: First row : different views of magnetic tracking sensors attached on UltraChin. Second row : Different parts of UltraChin and magnetic tracking sensor can be seen in figure.

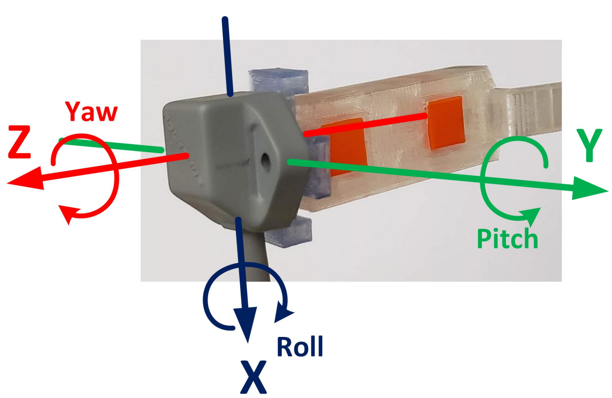

Figure 12: Tracking magnetic sensor was attached on UltraChin. Arrows show 6 degree of freedoms defined in our experiments.

ning session, users can check their face alignment with the camera using the red color guideline, which should always be between two markers. We simultaneously recorded acoustic data, superimposed video, individual video data from two RGB cameras (face-side and front-side view), real-time ultrasound frames, and tongue contour information for later experiments or follow-up study.

There are many methods and standards in the literature for testing L2 pronunciation acquisition methods [9, 11, 24]. It is possible to use the system for small numbers of L2 pronunciation training individuals [9] in a large classroom setting, either by providing individual ultrasound training to language instructors [61] or by presenting ultrasound videos as part of a blended learning approach [13], or even in a community-based settings [1]. For example, in [17], the previous ultrasound-enhanced system has been tested in several courses at UBC (named eNunciate). This kind of system is also tested for the training and revitalization of different indigenous languages [16]. The usability of ultrasound biofeedback in L2 pronunciation training has been comprehensively investigated in [11, 12].

Status of four screws	Max translational in milimeters			Max Rotational in degree		
	x	y	z	roll	yaw	pitch
Loose	$4.7 \pm 0.39mm$	$5.1 \pm 0.69mm$	$7.6 \pm 0.81mm$	$6.4 \pm 0.21°$	$4.1 \pm 0.46°$	$5.9 \pm 0.86°$
Tight	$3.4 \pm 0.18mm$	$3.5 \pm 0.72mm$	$6.1 \pm 0.15mm$	$5.6 \pm 0.59°$	$3.8 \pm 0.45°$	$4.7 \pm 0.91°$

Table 1: Maximum slippage of the UltraChin in 6DOF after 10 time testing on one participant. Values show the mean and standard deviation for each experiment. Screws of the UltraChin was loosely and tightly firm in two different experiments.

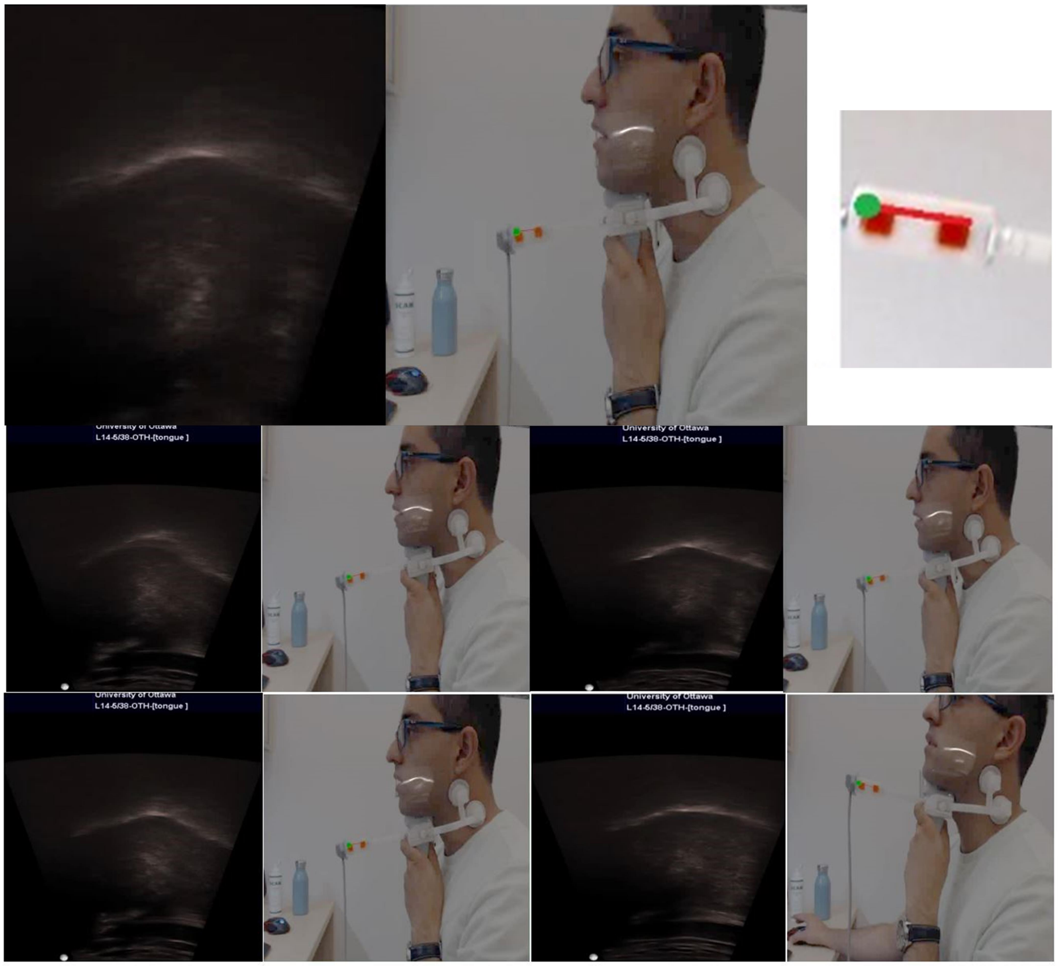

Figure 13: Sample frames of our real-time multimodal system. Thick white lines on the right-side images are extracted tongue contours from the corresponding left-side ultrasound images. Red line between two markers is illustrated as a guide.

Note that due to the limitation of this experiment, we can no conclude the effectiveness of our system on pedagogical aspects of L2 language, and linguistics experts should conduct a comprehensive collaborating user study. However, due to the lack of assessment facilities like a big classroom equipped with ultrasound machines, we followed the method in [9] for a participant experiment as a pilot evaluation study. In this technique, one approach is used repeatedly to measure the dependent variables from an individual. The dependent variables in this methodology consist of targets to be learned, such as vowels and consonants [9]. The main goal is to study articulator positions and segments, the accuracy of production, and speech intelligibility. Good candidates for ultrasound biofeedback are usually vowels, rhotic sounds, retroflex, velar and uvular consonants, and dynamic movements between tongue gestures [1].

Ultrasound has been utilized to teach individual challenging sounds, such as English /r/, in clinical settings [10, 24]. For this reason, we selected one individual participant to practice predefined sounds individually by comparing them with the pronunciation of the same statements by a native speaker. We utilized sample videos from the eNunciate project website UBC language department [47] as our truth pronunciation references. An Iranian L2 pronunciation learner volunteered to use our multimodal pronunciation system for ten sessions to improve pronunciation of /r/ sound. Each session contained 20 times repeating of /ri/, /ra/, and /ru/ and comparing with the video downloaded from [47]. Before the first session, we trained the participant for correct using our system and watching several training videos from the same website.

The benefits of our pronunciation system are not limited to only real-time and automatic characteristics. During pronunciation sessions, unlike other studies [15], there is no need for any manual synchronization. Furthermore, ultrasound frames, RGB video frames, audio data, overlaid images, and extracted contour information are recorded and visualized simultaneously. Our preliminary assessments showed that a language learner would fatigue slower than previous studies, in which the average time was 20 to 30 mins due to maintaining a relatively constant position [9]. In our system, non-physical restrictions such as using uniform backgrounds [18] in video recording have been addressed, and the system can be used in any room with different ambient features. Our system can provide researchers a real-time quantitative evaluation (such as mean sum of distances (MSD) in percentage) between tongue contours of language learner and teacher (requires the second ultrasound device or pre-recorded videos).
Testing the efficacy of our real-time automatic multimodal pronunciation system in detail remains in the early stages, and further research should be accomplished to create a fuller and more accurate assessment of our system with the collaboration of linguistics departments.

4 Discussion and Conclusion

In this study, we proposed and implemented a fully automatic and real-time modular multimodal ultrasound-enhanced pronunciation training system using several novel innovations. Unlike previous studies, instead of tracking the user's face or using tracking devices (see [44] for different tracking devices), the ultrasound probe position and orientation are estimated automatically using a 3D printable stabilizer (named UltraChin) and a deep learning model (named ProbeNet). ProbeNet was trained in advance on our dataset to track two markers on the UltraChin. This approach enables our pronunciation system to determine the optimum transformation quantities for multimodal superimposition as a user-independence system.
UltraChin makes the system universal for every ultrasound probe as well as invariant respect to the probe image occlusion. UltraChin errors due to the slippage of the device during a language pronunciation training session were within the standard range in the literature. At the same time, the pre-trained BowNet model [49], another deep learning model tracks, delineates, and highlights the tongue regions on ultrasound data. Different enhanced and transformed video frames from the different modules of our system are overlaid for illustration in the visualization module. Except for the preparation of training datasets, all modules in our system work automatically, in real-time, end-to-end, and without any human manipulation.
The application of our system can even be studied as visual biofeedback (VBF) for other applications like pronunciation training in different languages. Our system can be utilized for diagnosis and treatment planning of development speech disorders (SSDs), which is a common communication impairment in childhood who consistently exhibit difficulties in the production of specific speech sounds in their native language [62]. We believe that publishing our datasets, annotation package, deep learning architectures, and pronunciation training toolkit deployed on a publicly available Python programming language with an easy to use documentation will help other researchers in the different fields of linguistics.
Previous semi-automatic multimodal methods [26] revealed that language learners could understand the gestures of their tongue better in real-time using an ultrasound-enhanced multimodal visualization approach than previous recorded offline systems. Despite all the successful performance achievements of our proposed system, the development of our system is still in the early stages. An extensive pedagogical investigation of our pronunciation training system for teaching and learning should be accomplished to evaluate the efficiency and effectiveness of our system in different aspects of pronunciation training. Providing a comprehensive GUI for our system is also still under progress.

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Mapping a Continuous Vowel Space to Hand Gestures

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1 Introduction

Individuals with speaking disabilities often use Text-To-Speech (TTS) synthesizers for communication. However, users of TTS synthesizers often produce monotonous speech and the use of such synthesizers often renders lively communication difficult [1]. As a result, hand gestures have been used to successfully generate of speech [1, 2]. Fels and Hinton [2] designed Glove-TalkII that translates hand gestures to spoken English via an adaptive interface. The system allows users to generate an unlimited number of English vocabularies by controlling ten parameters of the speech synthesizer [2]. Each parameter maps to a different hand gesture or location, allowing the user's hands to act as an artificial vocal tract [2]. Another hand-gesture-to-sound mapping system developed by Kunikoshi et al. [1] maps a set of five hand gestures to the five vowels of Japanese with smooth transitions. However, both systems have their limitations. The first system uses extensive hand movements and is less intuitive for an interested layman. The second system is designed to synthesize speech sounds of only one language and uses distinct hand gestures to represent individual speech sounds, as a result of which, continuous change between two speech sounds cannot be intuitively represented by continuous hand movement.

The goal of this project is to develop a synthesizer for which hand movement can be used to control and produce a continuous vowel space more easily and intuitively. It also aims to make the synthesizer more user-friendly by providing real-time speech sounds as feedback, as well as an inverse model that visualizes hand gestures which are required for specific sounds.

2 Proposed method

2.1 Data collection

We use CyberGlove II, manufactured by Immersion Inc., to capture hand movements. It has 18 sensors that record information such as wrist flexion and bend and abduction of the fingers. This two-dimensional (2D) control of flexion and abduction allows the user to control the 2D formant space continuously. Figure 1 shows the hand gestures for [a] (fingers adducted, pointing upward) and [i] (fingers abducted, pointing downward). The elbow is fixed at rest position and utmost care is taken in order to avoid all other unintended motions.

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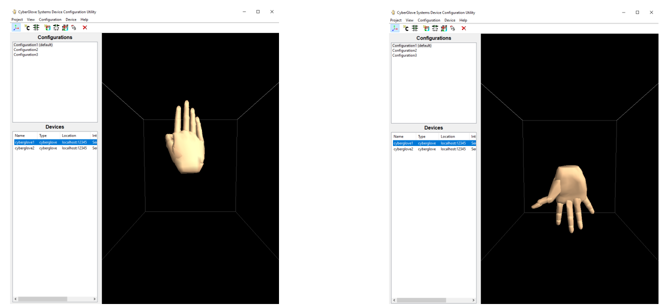

(a) Hand gesture for /a/ **(b)** Hand gesture for /i/

Figure 1: The Virtual Hand SDK of Cyberglove

2.2 Forward and inverse mapping between kinematics and acoustics

Wrist flexion and abduction of the index and pinky fingers are used to mapped linearly onto F1 and F2 respectively as shown below, which are formant values inherent to vowel sounds. Speech sounds are then synthesized using Vowel Synthesis in MATLAB [3].

$$F1 = \frac{F1\max - F1\min}{flexion\max - flexion\min} \times flexion + b1$$
$$b1 = F1\min - \frac{F1\max - F1\min}{flexion\max - flexion\min} \times flexion$$
$$F2 = \frac{F2\max - F2\min}{abduction\max - abduction\min} \times abduction + b2$$
$$b2 = F1\min - \frac{F2\max - F2\min}{abduction\max - abduction\min} \times abduction$$

A male adult user performs hand movements such as adducting and abducting four fingers together with bending the wrist up and down. Estimated F1 and F2 from hand movements are used as input in a vowel synthesizer to generate vowels. F0 is fixed as 100 Hz, and F3 is fixed as 2400 Hz.

In addition to the pilot results, more hand movements were mapped to different vowels. In order to facilitate the learning process of using CyberGlove to produce vowels, inverse modeling was designed to visualize hand movements needed to produce certain sounds. F1 and F2 values from a sequence of vowels of spoken English was extracted using FormantPro [4] and then converted to wrist flexion and finger abduction. The wrist flexion and figure abduction that being generated by users hand can be compared to those converted from inverse modeling. Thus, users is informed to perform in a more accurate way. Based on the linear regression analysis, the value of $b1$ and $b2$ were fixed at 482.64 and -332.79 respectively.

$$flexion = (F1 - b1) \times \frac{flexion\max - flexion\min}{F1\max - F1\min}$$
$$abduction = (F2 - b2) \times \frac{abduction\max - abduction\min}{F2\max - F2\min}$$

3 Experiments and results

The first and second formant frequencies used for synthesizing the outer cardinal vowels are depicted in Table 1.

Table 1: Formant frequencies

Vowels	F1	F2
[i]	270	2290
[ɑ]	730	1090
[æ]	660	1720
[u]	300	870

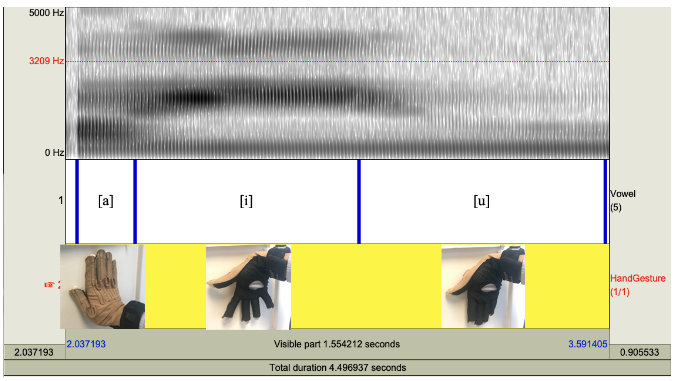

Figure 2: The spectrogram corresponding to [a], [i], [u] and respective hand gestures

Figure 2 shows the spectrogram of three vowels with smooth transition in between generated from vowel synthesizer with continuous hand movement as input. First layer in the figure presents the spectrogram, second layer shows segmentation, and third layer presents corresponding hand gesture.

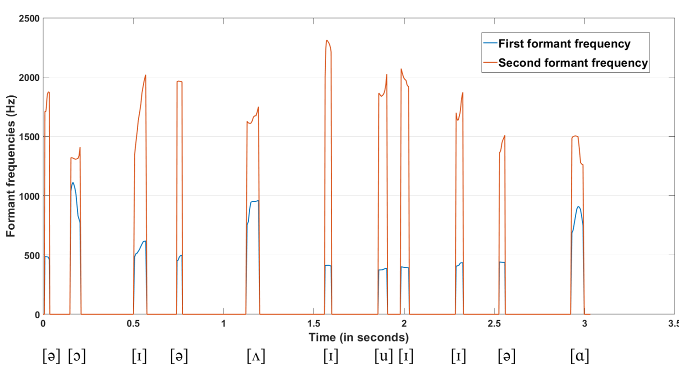

Figure 3: First and second formant frequency corresponding the vowels of the sentence "The north wind and the sun were disputing which one was the stronger"

Figure 3 shows F1 and F2 values of vowels in an English sentence "The north wind and the sun were disputing which one was the stronger". Further, those values were converted to wrist flexion and figure abduction as shown in Figure 4. Positive wrist flexion value indicates hand and fingers were pointing upward, and negative wrist flexion value indicates hand and fingers were pointing downward to the ground.

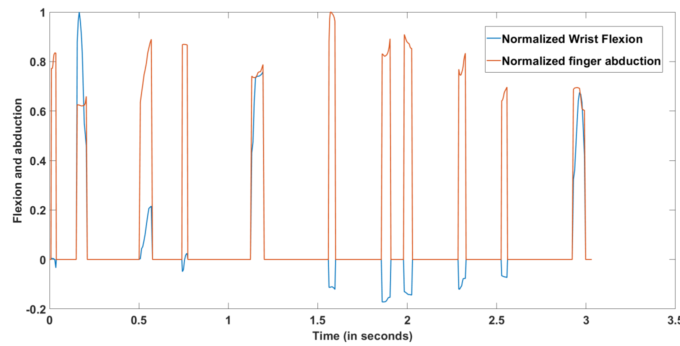

Figure 4: Normalized wrist flexion and finger abduction values for synthesizing vowels of the sentence "The north wind and the sun were disputing which one was the stronger"

4 Discussions and conclusions

This interface primarily uses the CyberGlove as an input device to map continuous hand gestures to English vowels, but, can be easily extended to vowels of any other language. A major advantage of the interface is that its scope is not limited by any particular vocabulary, as it uses formant based vowel synthesis and hence allows synthesis of vowels throughout the vowel quadrilateral, rather than a discrete synthesis of selected vowels. Since this involves a direct one-to-one mapping of the control dimensions to the formant frequencies, it is very easy to learn. Besides, the gestures are intuitive even for a layman without linguistic knowledge, thereby making the interface sufficiently user-friendly. It is also efficient in mapping the gesture transitions accurately to the targeted dipthongs (e.g., in boy), and to a targeted vowel sequence (e.g., in Hawaii). Further step could be to make this hand gesture to speech sound mapping real-time, such that users can produce speech sounds simultaneously with moving hands.

Acknowledgments

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Passing of Tim Kelsall (April 28,1951 – March 13, 2020)

Tim Kelsall, a former employee of Hatch, passed away on March 13, 2020, at the age of 68.

Tim died peacefully in his sleep, one year after being diagnosed with pancreatic cancer. He leaves his wife and best friend Debbie and much-loved children John (Faryn) and Heather (Justin). Sadly missed by his mother Diana, brother Brian (Ella) and sister Jill (Stephen). Predeceased by his father John (2013).

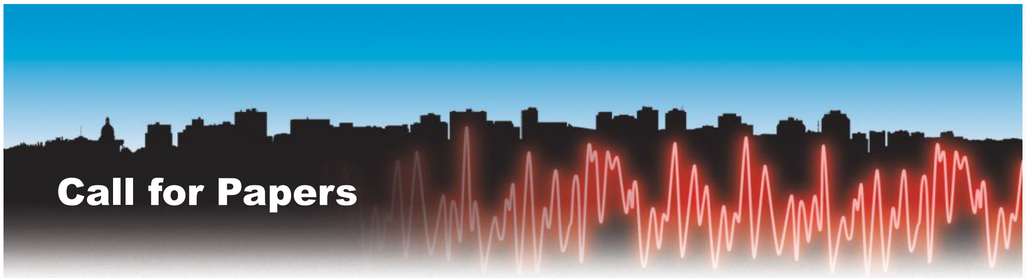
Tim graduated from the University of Toronto with a degree in Applied Physics in 1973 and with a Master's degree from the University of Toronto's Institute for Aerospace Studies in 1975. In 1978, Tim joined Hatch after developing some of the founding noise emission requirements and reporting standards with the Ontario Ministry of the Environment and Energy. Some of these guidelines continue to be used today.

Tim has been the face of Hatch noise and vibration for over 40 years, improving the practices' global awareness within Hatch and amongst our clients. Over the years, Tim became world renown as an industrial noise subject matter expert and a beacon that guided clients through the ever-increasing demand to address occupational noise and vibration exposure.

Tim was known for his passion to improve workplace safety by tackling the difficult and commonly underfunded need to eliminate occupational hearing loss one client at a time. Tim will be remembered for his positive attitude, love for sailing, skiing, fitness, and most of all; coming into the office to practice the science and engineering of industrial noise control.

He also amassed an impressive collection of single malt scotch! Most of all he loved to spend time with his family, who will miss him very much.

At Tim's request there will be **no** funeral. If you wish, donations can be made to the **Friends of Killarney Park** or **a charity of your choice**.



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Such an offer will only repeat in 7 to 9 years – be sure to submit now!

Numéros spéciaux portant sur des sujets régionaux

Comme vous le savez, l'acoustique donne matière à plusieurs sujets d'ordre général qui créé des centaines d'emplois au Canada et ce, dans différents secteurs tels que l'éducation, la recherche, la consultation professionnelle ou d'autres. Afin de bien refléter cette diversité et en vue de faire connaître d'avantage les professionnels de notre région qui œuvrent dans ce domaines, l'Acoustique canadienne fait un appel à soumettre une série d'articles provenant de personnes, groupes ou compagnies qui font partie d'une même grande région du Canada.

À l'heure actuelle, les numéros spéciaux régionaux de l'Acoustique canadienne ont eu lieu en juin 2015 (Montréal), juin 2016 (Toronto), juin 2017 (Halifax) et juin 2018 (Colombie Britannique), tandis que juin 2020 sera consacré à la province de l'Alberta!

Comment en faire partie?

Pour contribuer à un de ces numéros « régionaux », les auteurs sont invités à soumettre un article (de 2 pages maximum), sous la rubrique « Numéro spécial » dans notre système en ligne au http://jcaa.caa-aca.ca avant le **30 avril 2020**. Le premier auteur devra faire partie de la province d'Alberta. Il est possible de soumettre un même article dans les 2 langues officielles.

Chaque article sera révisé par le comité éditorial de l'Acoustique canadienne qui veillera à ce que les politiques de publications de la revue soient respectées (contenu original, contenu non commercial, etc. – voir les politiques de la revue pour de plus amples détails) tout en accueillant les articles qui font la promotion de l'expertise des auteurs, des services offerts par les compagnies, les réussites de consultants et autres sujets du même ordre.

Un vrai « répertoire régional » dans lequel vous voulez paraître!

Chacun de ces numéros spéciaux régionaux pourra être considéré comme un répertoire des noms et services locaux liés à l'acoustique. Ils seront publiés en format papier et envoyés à tous les membres nationaux et internationaux de l'ACA. Une version électronique sera aussi disponible en ligne sur le site internet de la revue. Le contenu de ces numéros sera indexé, donc facilement trouvable au moyen de moteurs de recherche majeurs, tels Google, Bing, etc.). Les auteurs sont invités à bien choisir les mots clefs pour maximiser la visibilité de leur article. Des opportunités de publicité ad hoc seront offertes pour jumeler chaque article avec une page complète de publicité.

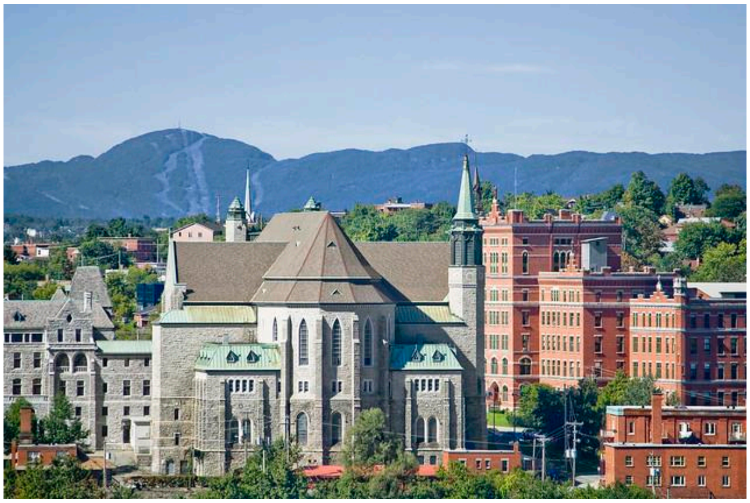
Pour toutes questions, vous pouvez communiquer avec Jessie Roy (jessie.roy@rwdi.com), Benjamin Tucker (bvtucker@ualberta.ca), or Corja Buma (meanu@ualberta.ca). Pour réserver un espace de publicité dans un de ces numéros spéciaux, veuillez communiquer avec notre coordonnateur (advertisement@caa-aca.ca).

Une telle offre ne se reproduira pas avant 7 ou 9 ans, assurez-vous d'en profiter maintenant!

Announcement

ACOUSTICS WEEK IN CANADA

Sherbrooke (Québec) October 7-9, 2020



View of Mont-Orford from downtown Sherbrooke

Acoustics Week in Canada 2020 will be held on October 7-9, in Sherbrooke, Québec.

You are invited to be part of this three-day conference featuring the latest developments in Canadian acoustics and vibration. Sherbrooke is well known in acoustics for the Groupe d'Acoustique de l'Université de Sherbrooke (GAUS) founded in 1984.

The conference will be an excellent opportunity to visit or rediscover the GAUS during the International Year of Sound!

The keynote talks and technical sessions will be framed by a welcome reception, conference banquet, Acoustical Standards Committee meeting, technical tour and an exhibition of products and services related to the field of acoustics and vibration.

Take a few days before or after the conference to enjoy the area and the cultural activities! Especially have a look to the beautiful surrounding nature during Fall colors with Mont-Bellevue downtown and the nearby 'Mont-Orford' National Park. Three other parks can also be found within a radius of 100 km.

Various demos and activities will be held at the Groupe d'Acoustique de l'Université de Sherbrooke (GAUS) and at Université de Sherbrooke campus - A series of innovative workshop activities will be a part of the program; we are open to proposals along this line (challenges, measurements, simulations).

Venue and Accommodation

The conference will be held at the Hotel Delta by Marriott in Sherbrooke. A block of rooms in the hotel will be available at a special rate of 155$/night. This rate is extended to stays two days prior and two days after the conference, and each room can be shared across up to 4 people. Complimentary city bus passes will be offered to all the participants to promote the use of public transport during the conference. A shuttle is also available to provide a direct link between International Montréal Trudeau Airport and the conference venue. Please refer to the conference website for further details and registration: https://awc.caa-aca.ca/index.php/AWC/AWC20

Plenary, Technical and Workshop Sessions

Plenary, technical and workshop sessions are planned throughout the conference. Each day will begin with a keynote talk of broader interest and relevance to the acoustics community. Technical sessions are planned to cover all areas of acoustics including:

AEROACOUSTICS / ARCHITECTURAL AND BUILDING ACOUSTICS / BIO-ACOUSTICS AND BIOMEDICAL ACOUSTICS / MUSICAL ACOUSTICS / NOISE AND NOISE CONTROL / PHYSICAL ACOUSTICS / PSYCHO- AND PHYSIO-ACOUSTICS / SHOCK AND VIBRATION / SIGNAL PROCESSING / SPEECH SCIENCES AND HEARING SCIENCES / STANDARDS AND GUIDELINES IN ACOUSTICS / ULTRASONICS / UNDERWATER ACOUSTICS

A General Public Session

A general public session is currently planned on the afternoon of the last conference's day and linked to the International Year of Sound, a global initiative to highlight the importance of sound and related sciences and technologies for all in society (https://sound2020.org/). This event will be held on Université de Sherbrooke campus and opened to scholars and to the population. The organizing committee welcomes any proposal for this session, a rare occasion of explaining our everyday job and implications for society.

Exhibition and Sponsorship

The conference offers opportunities for suppliers of products and services to engage the acoustic community through exhibition and sponsorship.

The tabletop exhibition facilitates in-person and hands-on interaction between suppliers and interested individuals. Companies and organizations that are interested in participating in the exhibition should contact the Exhibition and Sponsorship coordinator for an information package. Exhibitors are encouraged to book early for best selection.

Anechoic room and wind-tunnel opening at GAUS

The conference will be offering sponsorship opportunities of various conference features. In addition to the platinum, gold and silver levels, selected technical sessions, social events and coffee breaks will be available for sponsorship. Additional features and benefits of sponsorship can be obtained from the Exhibition and Sponsorship coordinator and on the conference website. Demos can also be organized at GAUS.

Students

Students are strongly encouraged to participate. Students presenting papers will be eligible for one of three 500$ Best Presentation Student prizes to be awarded. Conference travel bursaries will also be available to those students whose papers are accepted for presentation.

For Registration Details,

For registration details please refer to the conference web site: https://awc.caa-aca.ca/index.php/AWC/AWC20

Contacts

Conference Chair:
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Technical co-Chairs:
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Sebastian Ghinet
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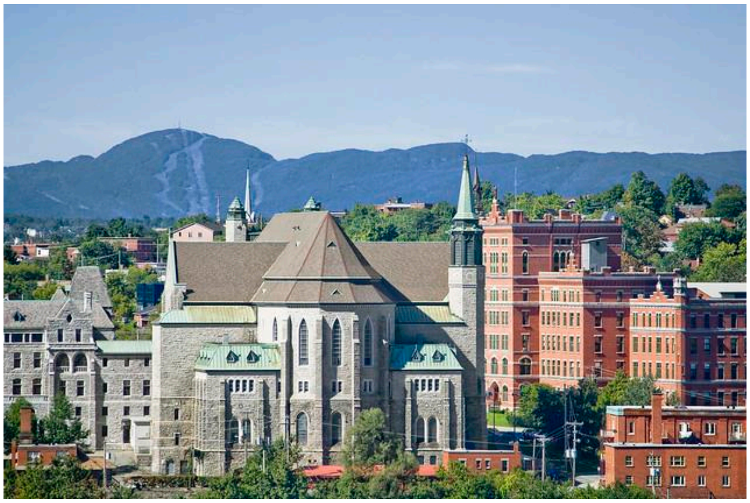
Exhibits and Sponsorships:
Julien Biboud
(Julien.Biboud@mecanum.com)

Enjoy the Mont Bellevue in the center of Sherbrooke during Fall

Appel à communication

SEMAINE CANADIENNE D'ACOUSTIQUE

Sherbrooke (Québec) 7-9 Octobre 2020



Vue du Mont-Orford depuis le centre-ville de Sherbrooke

La Semaine canadienne d'acoustique 2020 se tiendra du 7 au 9 octobre 2020 à Sherbrooke, Québec.

Nous vous invitons à prendre part à cette conférence de trois jours sur les derniers développements en matière d'acoustique et de vibrations au Canada. Sherbrooke est reconnue en acoustique pour le Groupe d'Acoustique de l'Université de Sherbrooke (GAUS) fondé en 1984.

La conférence sera le moment idéal pour visiter ou redécouvrir le GAUS durant l'Année Internationale du Son !

Les exposés principaux et les séances techniques seront encadrés par une réception de bienvenue, un banquet, une réunion du comité des normes acoustiques, une visite technique et une exposition de produits et services liés au domaine de l'acoustique et des vibrations.

Prenez quelques jours avant ou après la conférence pour profiter de la région et des activités culturelles ! Découvrez la nature environnante durant la flambée des couleurs d'automne, avec la proximité du Parc National du Mont-Orford. Trois autres parcs nationaux sont accessibles dans un rayon de 100 km.

Diverses démonstrations et activités seront organisées au sein du Groupe d'Acoustique de l'Université de Sherbrooke (GAUS) et sur le campus principal de l'université de Sherbrooke. Des ateliers participatifs seront intégrés dans le program-me; nous sommes ouverts à toute proposition (concours, mesures, simulations).

Lieu et hébergement

La conférence aura lieu au Centre de congrès de l'Hôtel Delta Sherbrooke par Marriott. Un bloc de chambres dans l'hôtel sera disponible à un tarif spécial de 155$ par nuit (valable deux jours avant et deux jours après la conférence, et chaque chambre peut être partagée par 4 personnes au maximum). Des passes de bus seront offertes à tous les participants afin de favoriser l'usage du transport en commun durant la conférence. Une navette directe entre l'aéroport international Trudeau de Montréal et le lieu de la conférence est également accessible sur demande. Veuillez consulter le site Web de la conférence pour plus de détails et pour l'inscription: http://awc.caa-aca.ca/AWC/AWC20

Séances plénières, techniques et ateliers

Des séances plénières, techniques et des ateliers sont prévus tout au long de la conférence. Chaque journée débutera par une plénière d'un intérêt et d'une pertinence plus larges pour la communauté de l'acoustique. Des sessions techniques sont prévues pour couvrir tous les domaines de l'acoustique, y compris :

AÉROACOUSTIQUE / ACOUSTIQUE DU BÂTIMENT ET ARCHITECTURALE / BIOACOUSTIQUE / ACOUSTIQUE BIOMÉDICALE / ACOUSTIQUE MUSICALE / BRUIT ET CONTRÔLE DU BRUIT / ACOUSTIQUE PHYSIQUE / PSYCHOACOUSTIQUE / CHOCS ET VIBRATION / LINGUISTIQUE / AUDIOLOGIE / ULTRASONS / ACOUSTIQUE SOUS-MARINE / NORMES EN ACOUSTIQUE

Une session grand public

Une session grand public est planifiée en après-midi du dernier jour de la conférence, et liée à l'année internationale du son, une initiative globale destinée à illustrer l'importance du son et de ses sciences et technologies dans la société (https://sound2020.org/). Cet évènement se déroulera sur le campus de l'Université de Sherbrooke et sera ouvert aux scolaires et à la population. Le comité organisateur est ouvert à toute proposition pour cette session, une rare occasion d'expliquer notre travail et ses implications pour la société.

Exposition et parrainage

La conférence offre aux fournisseurs de produits et de services la possibilité de faire participer la communauté acoustique par l'exposition et le parrainage.

L'exposition sur le plateau facilite l'interaction en personne des fournisseurs et des personnes intéressées. Les entreprises et organisations désirant participer à l'exposition doivent contacter le coordonnateur de l'exposition et du parrainage pour obtenir un dossier d'information. Les exposants sont encouragés à réserver tôt pour obtenir de meilleures opportunités.

Salle anéchoïque et soufflerie au GAUS

La conférence offrira des possibilités de parrainage de divers évènements de la conférence. Outre les niveaux platine, or et argent, des séances techniques, des événements sociaux et des pauses café seront disponibles pour le parrainage. Les commanditaires peuvent placer leur logo sur le site Web de la conférence dans les 10 jours suivant leur parrainage. Les caractéristiques et avantages supplémentaires du parrainage peuvent être obtenus auprès du coordonnateur des expositions et des commandites ou sur le site Web de la conférence. Des démonstrations pourront aussi être organisées au GAUS.

Les étudiants

Les étudiants sont fortement encouragés à participer. Les étudiants qui présenteront seront admissibles à l'un des trois prix de 500 $ pour les meilleures présentations. Des subventions de voyage seront également offertes aux étudiants dont les communications sont acceptées pour présentation.

Plus d'informations

Pour plus d'information sur l'inscription veuillez consulter le site Web de la conférence : http://awc.caa-aca.ca/AWC/AWC20.

Contacts

Président de la conférence :
Olivier Robin
(Olivier.Robin@USherbrooke.ca)

Présidents techniques :
Patrice Masson and
Sebastian Ghinet
(Patrice.Masson@USherbrooke.ca)
(Sebastian.Ghinet@nrc-cnrc.gc.ca)

Exposants et commandites :
Julien Biboud
(Julien.Biboud@mecanum.com)

Appréciez le Mont Bellevue au centre de Sherbrooke durant l'automne

SPONSORSHIP PROGRAM

Why should you support AWC congress?

AWC will allow you to increase your visibility with a large number of students in acoustics and vibration who will soon buy your products or services, as well as many engineers and scientists from multiple businesses and universities.

We offer many visibility possibilities in function of which package you choose, such as:

- Color ad in the journal Canadian Acoustics (in all four issues of 2021)
- www.awc.caa-aca.ca website
- Stand up banners with your graphic, logo and advertising material
- Acknowledgment in the journal Canadian Acoustics
- Your company's brochure in the conference handouts
- Recognition by the CAA committee

Available Programs

Official Diamond Sponsor | CAD$ 7,500

(Exclusive opportunity)

As the official AWC Diamond Sponsor, you will have the first choice for the location of your booth, and you will benefit of all the following advantages:

- Exhibition booth* ($750)
- Two (2) full conference registration ($450)
- One (1) full page color ad in the journal (in all four issues of 2021, value $1200)
- Two (2) stand up banners with your graphic, logo and advertising material (yours to take after the conference, value $500)
- Large display of your name and logo in the conference proceedings issue of the journal *Canadian Acoustics*, your company's brochure in the conference handouts and recognition by the CAA committee
- Four (4) banquet tickets to the banquet night ($300)

Gold Sponsor | CAD$ 5,000

As an AWC Gold Sponsor, you will have the second choice for the location of your booth, and you will benefit of all the following advantages:

- Exhibition booth* ($750)
- One (1) full or two one day conference registration ($450)
- ½ page color ad in the journal (in all four issues of 2021, value $700)
- One (1) stand up banners with your graphic, logo and advertising material (yours to take after the conference, value $250)
- Medium display of your name and logo in the conference proceedings issue of the journal *Canadian Acoustics*, your company's brochure in the conference handouts, and recognition by the CAA committee

Silver Sponsor | CAD$ 3,000

As an AWC Silver Sponsor, you will have the third choice for the location of your booth, and you will benefit of all the following advantages:

- Exhibition booth* ($750)
- One (1) full or two (2) one day conference registration ($450)
- ¼ page color ad in the journal (in all four issues of 2021, valued $500)
- Small display of your name and logo in the conference proceedings issue of the journal *Canadian Acoustics*, your company's brochure in the conference handouts, and recognition by the CAA committee

Additional Sponsor Opportunities

Don't miss the opportunity to sponsor the congress events:

- Coffee break ($800) - Four (4) available
- Lunch ($2,500) - Two (2) available
- Welcome cocktail ($2,500) - One (1) available
- Cocktail supper ($4,500) - One (1) available

*Exhibition booth includes all the followings:

- Two (2) complimentary exhibitor badges which include access to the exhibition area, the lounge area, covers for lunches and refreshments
- Two (2) city bus passes
- Two (2) accesses to the welcome cocktail
- One (1) access to the cocktail supper

Other Information

Advertisement in the Journal *Canadian Acoustics*

- Deadline to submit your ad is July 31st, 2020 for the September issue.
- Ads dimensions should be as the following:
  - Full page - PDF, PNG or JPG - 7.0" (w) x 9.5" (h) Portrait - 300 DPI min
  - Half page - PDF, PNG or JPG - 7.0" (w) x 4.75" (h) Landscape - 300 DPI min
  - Quarter page - PDF, PNG or JPG - 3.5" (w) x 4.75" (h) Portrait - 300 DPI min

Corporate Logo and Stand Up Banner Graphic

All corporate logos and graphics must be provided in vector format. If not available, high resolution format can also be accepted (at least 300 DPI at 10").

Payment Information

Taxes

All prices include a 14.975% taxes.

Payment

After booth and representatives registration, you will receive a confirmation email including the payment procedure.

Cancellation Policy

All cancellation must be submitted in writing via e-mail at:

- julien.biboud@mecanum.com
- Before July 1st, 2020 receive a 50% refund
- No refunds will be made after July 1st, 2020

CANADIAN ACOUSTICS ANNOUNCEMENTS - ANNONCES TÉLÉGRAPHIQUES DE L'ACOUSTIQUE CANADIENNE

Looking for a job in Acoustics?

There are many job offers listed on the website of the Canadian Acoustical Association!

You can see them online, under http://www.caa-aca.ca/jobs/

August 5th 2015

Acoustics Week in Canada 2020

AWC 2020 will be held October 7 – 9, 2020 in Sherbrooke (Québec) with Dr. Olivier Robin as General Chair, as well as Prof. Patrice Masson and Dr. Sebastian Ginet as Scientific Chairs. https://awc.caa-aca.ca/index.php/AWC/AWC20

May 3rd 2019

Acoustics Week in Canada 2021

AWC 2021 will be held in St-John's (Newfoundland) with Profs. Benjamin Zendel and Len Zedel as co-chairs. https://awc.caa-aca.ca/index.php/AWC/AWC21

May 3rd 2019

2020: International Year of Sound

The International Year of Sound (IYS 2020) is a global initiative to highlight the importance of sound in all aspects of life on earth and will lead towards an understanding of sound-related issues at the national and international level.

Inspired by the achievements of La Semaine du Son (The Week of Sound), and following naturally as an important contribution to UNESCO Resolution 39 C/49 25 September 2017 on "The Importance of Sound in Today's World: Promoting Best Practices", the International Commission for Acoustics (ICA) is mobilizing its Member Societies and International Affiliates to promote best practices in sound during the year of 2020 to create an International Year of Sound (IYS 2020). For more info, visit http://sound2020.org/

May 3rd 2019

9th Forum Acusticum - April 20 to 24 2020 -Lyon, France.

The European Acoustical Association together with the French Acoustical Society is pleased to invite you to the 9th Forum Acusticum to be held in world heritage city of Lyon-France April 20-24, 2020.

The 9th Forum Acusticum will take place from April 20 to 24 2020 in Lyon, France. More than 1100 delegates from all over the world are expected to participate in more than 100 structured sessions. An exhibition area is available for companies to display their skills and products in noise and vibration. Several sponsorship formulas are also possible. We would like to draw your attention to the next deadline of 1st December for early registration to the exhibition at a reduced rate. Details are available in the sponsorship booklet on the exhibition web page of the congress: https://fa2020.universite-lyon.fr/ Abstract submission deadline Dec 1st 2019 Notification of acceptance Jan 15th 2019 Early bird registration Feb 15th 2019

October 28th 2019

À la recherche d'un emploi en acoustique ?

De nombreuses offre d'emploi sont affichées sur le site de l'Association canadienne d'acoustique !

Vous pouvez les consulter en ligne à l'adresse http://www.caa-aca.ca/jobs/

August 5th 2015

Semaine canadienne de l'acoustique 2020

L'AWC 2020 se tiendra du 7 au 9 octobre 2020 à Sherbrooke (Québec) avec le Dr Olivier Robin comme président général, ainsi que le Prof. Patrice Masson et le Dr Sebastian Ginet comme présidents scientifiques. https://awc.caa-aca.ca/index.php/AWC/AWC20

May 3rd 2019

Semaine canadienne de l'acoustique 2021

L'AWC 2021 aura lieu à St-John's (Terre-Neuve). Benjamin Zendel et Len Zedel sont co-présidents. https://awc.caa-aca.ca/index.php/AWC/AWC21

May 3rd 2019

9ème édition du Forum Acusticum - du 20 au 24 Avril 2020 - Lyon, France.

L'Association Européenne d'Acoustique et la Société Française d'Acoustique ont le plaisir de vous inviter à la 9ème édition du Forum Acusticum qui se déroulera à Lyon du 20 au 24 Avril 2020. C'est un congrès joint avec le 15ème Congrès Français d'Acoustique.

October 28th 2019

MEMBERSHIP DIRECTORY 2019 - ANNUAIRE DES MEMBRES 2019

This member directory is generated from the Canadian Acoustical Association membership database records. Please feel free to update or correct this information directly on http://jcaa.caa-aca.ca.

Ce répertoire des membres est généré à partir des informations de la base de données des membres de l'Association canadienne d'acoustique. Mercci de mettre à jour ou corriger toute information directement sur http://jcaa.caa-aca.ca.

Code	Subscription type	Type d'inscription
1	Individual Member	Membre individuel
2	Student Member	Membre étudiant
3	Indirect Subscriber (Canada)	Abonné institutionnel indirect (Canada)
4	Sustaining Subscriber	Abonné de soutien
5	Indirect Subscriber (USA)	Abonné institutionnel indirect (É-U)
6	Indirect Subscriber (International)	Abonné institutionnel indirect (International)
7	Emeritus Member	Membre Emeritus
8	Advertiser (Full-Page) (1 year)	Publicité (1 page)
10	Direct Subscriber	Abonné institutionnel - Direct
11	Courtesy	Membre de courtoisie

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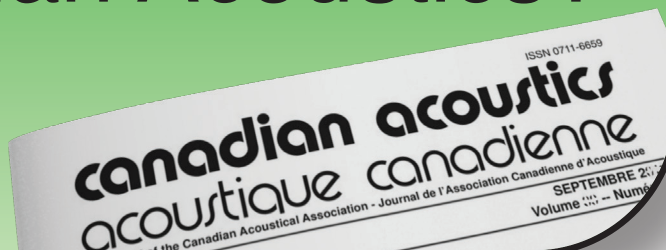

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