Vibroacoustic modeling of an *in vivo* human head wearing a hearing protection device using the finite element method

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Summary

One of the reasons why hearing protectors are not fully efficient at protecting against noisy environments is the acoustical discomfort they induce. This discomfort may incite an individual to wear his protector incorrectly or to remove it, thereby reducing its performance. The acoustical discomfort depends on the acoustic pressure value at the eardrum of the protected ear. To reduce it efficiently, a tool for the acoustical design of the hearing protector device (HPD) allowing for determining this acoustic pressure, may prove to be useful. This paper presents the methodology to develop a unique and realistic numerical Vibroacoustic Model (VM) in the audible frequency range of a human head wearing an HPD together with an associated instrumented Experimental Anatomical Phantom (EAP). The VM consists of a 3D finite element model of the head of a living subject wearing an HPD reconstructed from medical images. This model will be validated and calibrated step by step against an EAP made up of synthetic materials with average mechanical properties. It will then be calibrated against the human subject from which the VM is the replica. A new EAP will be fabricated based on the updated mechanical properties of the calibrated VM. Finally, it will be exploited to study a variety of earplugs and earmuffs together with the sound transmission mechanisms through the head/HPD system. Preliminary results on some stages of the VM development are also presented. A registration method applied on medical images of a simplified EAP of the external ear without and with earplugs show to which extent the latter can deform the ear canal. The deformed shape of earplugs can also be identified. Comparisons between the predicted sound attenuation of a commercial earmuff and experimental data in a simplified configuration are presented to evaluate an improved earmuff finite element model.

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1. Introduction[1]

Hearing protection devices (HPD) are often worn to protect workers from noisy environments. However, even if the worker wearing them knows how to properly install them, the effectiveness of this solution is still not ensured mainly because of physical, acoustical, functional and psychological discomforts [1,2]. These discomforts can cause the individual to mishandle or remove his protection, thus reducing the effective attenuation and the wearing time of the HPD and consequently its performance. Of these various sources of discomfort, the acoustical one plays a particularly important role. It depends on the value of the sound pressure at the eardrum. To effectively reduce it, an HPD design tool allowing for predicting this sound pressure and understand how the sound energy propagates in the system head / protector is essential. A tool integrating all the physical complexities of this system is currently not available. The general long-term goal of this research is to develop computational tools and test benches (augmented artificial test fixtures) to help design various effective and comfortable HPDs (earmuffs, earplugs,...), adapted to the people wearing them and to the sound environment in which they evolve (stationary noise, impulse, ...). This paper focuses on acoustical comfort by studying the steady state sound transmission through an HPD coupled to a human head.

Regarding the numerical modeling of the vibroacoustic behavior of a human head equipped with a HPD, past studies have been interested in predicting the sound attenuation or the occlusion effect (OE) of earplugs [3,4], the effect of inserting an earplug in the earcanal on the pressure in the cochlea [5], the effectiveness of helmets with respect to the bone conduction of impulsive noises via the assessment of pressure in the brain [6]. However, either their work is based on a simplified geometry of the head (i) where only the OE is considered (ear canal integrating the surrounding tissues, an impedance model for the eardrum but no middle ear and internal ear) [3,4], (ii) where the complete hearing system is considered but hypotheses simplifying the interaction between the HPD and the ear canal are made (no surrounding tissue) [5], or these works focus more on HPDs like helmets subject to impulse noise [6]. It should be emphasized that some partial validations of finite element (FE) head model with HPD were performed compared to a very realistic physical head simulator made from medical images [6,7]. In summary, for the most advanced researches, few detailed models are provided because the research was conducted in a military framework. In addition, these studies suffer from a lack of rigorous validation of FE models compared to experimental anatomical phantoms (EAP) or individual measurements on human subjects (head models are not calibrated). Finally, none focused on the sound attenuation or occlusion effect induced by earplug, earmuffs or dual protection-like systems, considering the head in all its complexity. Therefore there are shortcomings in existing models both in terms of prediction of the sound pressure at the eardrum of a protected ear and their in-vivo validation or with respect to EAP.

Regarding the literature about the numerical modeling of HPDS, FE type numerical models have been proposed to describe the vibroacoustic behavior of earmuffs [8,9] and earplugs [3,8,10–12] coupled to a synthetic outer ear of realistic or simplified geometry, consisting of a circular cylinder ear canal with or without artificial tissue, acoustically or mechanically excited. With regard to earmuffs, few models have been proposed and there are still significant differences between predictions and measurements in certain frequency zones, due to the inadequacy of the behavioral model of the cushion, as well as the poor representation of the mechanical couplings between earmuff components. Previously developed earplug models provide trends for groups of human subjects for specific earplugs but they have never been validated against measurements on a particular subject for a wide variety of earplugs. In addition, the effect of the respective deformations of a real auditory canal and of the earplug inserted therein, as well as the local variations of the associated properties, are poorly known and generally neglected.

To address the aforementioned issues, a research project on the prediction of the vibroacoustic response of a human head coupled with an HPD has started recently. This paper aims at describing this project in more details and presenting the latest advances. The paper is organized as follows. First the methodology to develop a unique and realistic numerical Vibroacoustic Model (VM) in the audible frequency range of an *in vivo* human

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head wearing an HPD together with an associated instrumented EAP is presented. The associated scientific and technical challenges are also emphasized. Preliminary results on some stages of the VM development are also shown. For example, a registration method which consists in moving and/or deforming a source image to match a target image has been applied on medical images of a simplified EAP of the external ear without and with earplugs and shows to which extent the latter can deform the ear canal. The deformed shape of earplugs can also be identified. Another example deals with a comparison between the predicted sound attenuation of a commercial earmuff and experimental data in a simplified configuration to evaluate an improved earmuff FE model.

2. Methodology

This research is divided into three specific tasks (1) Development of a numerical VM of a human head coupled to a custom earplug with known properties (2) Improvement of HPDs VM (3) Evaluation and exploitation of VM of the head coupled to a variety of HPDs.

2.1. Development of a numerical VM of an *in vivo* human head coupled to a custom earplug with known properties

2.1.1. Head and hearing system geometrical model

The geometrical model of the head and complete hearing system of an adult volunteer will be reconstructed using medical images obtained from both tomodensitometry and Magnetic Resonance Imaging scans. All relevant anatomical structures that can play a role in the associated elasto-acoustic problem (outer ear, middle ear, inner ear, skull, brain, etc.) will be considered. Appropriate documents have been submitted to the CRCHUM/ÉTS Clinical Research Ethics Boards for obtaining the certificate of ethics. Both MRI and Cone-Beam Computed Tomography (CBCT) scans of the human subject with and without earplug will be performed. MRI scan will be carried out for the entire head including the hearing system. This will lead to images of isotropic resolution 0.8mm. MRI is a particularly efficient technique to detect soft tissues (ex fat, skin, brain, etc.). It allows for a partial identification of the bony structures of the head. However the air contained in the ear canal and the bony part close to the eardrum cannot be distinguished since the skin thickness in this zone is smaller than the MRI resolution, unless the ear canal is filled with oil for example. It is therefore difficult to clearly distinguish the part of the ear canal in the vicinity of the eardrum. MRI must then be combined with another imaging technique with a finer resolution so that the details of the hearing system including the external, middle and internal ear together with the bony structure can be segmented. The segmentation consists in partitioning regions of an image sharing common features. These will be obtained by a CBCT scan which causes much less radiation exposure than CT-scan. The best resolution provided by the available CBCT scanner at the CRCHUM is 125 μm by targeting the ear region. CBCT is particularly appropriate to see bony structures. However, while soft tissues (including the eardrum) can still be identified in the images, it is not currently possible to separate skin and cartilage. An ongoing research at the CRCHUM aims at improving the CBCT image reconstruction performance to solve this issue. An alternative is to make assumptions regarding the skin layer shape according to published anatomical data. Note that the largest field of view provided by the CBCT scanner is not sufficient for scanning a whole adult head of normal size and MRI supplementary images are therefore required. These MRI images of the head will be combined with the CBCT images of the hearing system using image registration based on mutual information of the two datasets. Morphing techniques based on the deformation of a database of reference typical anatomical structures are also envisaged [13]. Figure 1 displays a preliminary reconstruction of the head and the outer ear of a human subject without earplug based on MRI images solely.

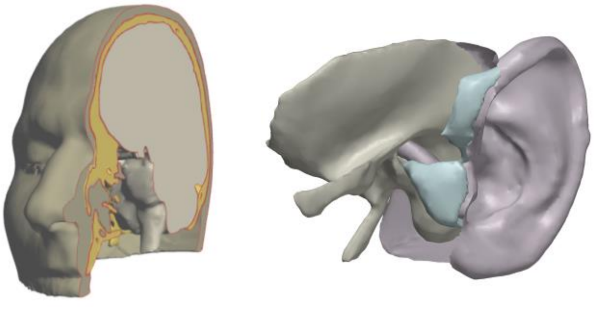

Figure 1. 3D reconstruction of the head (left) and outer ear (right) of an *in vivo* human subject reconstructed from MRI images

The medical image dataset can be used to assess the deformation of both the ear canal walls and the earplug due to its insertion. In Figure 2, a registration method has been applied on MRI images of the external ear of a participant without and with earplugs and shows to which extent the latter can deform the ear canal [14].

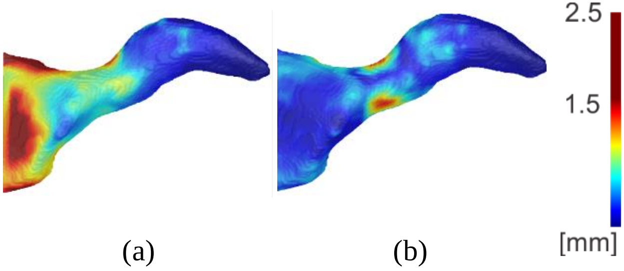

Figure 2. Surface plots of the displacement field modulus of the ear canal deformed by (a) silicone custom molded and (b) Pushin earplugs. The left and right parts of the surface plots refer to the entrance and the end of the ear canal respectively.

The impact of this deformation in the modeling process has not been investigated numerically yet. The insertion of the earplug in the ear canal induces of course a modification of the ear canal surrounding tissues and earplug geometries but also a change of the mechanical properties of both the earplug and the surrounding ear canal skin. A sensitivity analysis of the predicted sound pressure in the ear canal to each of these parameters could be performed to assess their impact.

2.1.2. Properties of tissues

The head consists of solid structures (skull bones, cartilage, skin, elements of the hearing system (e.g. ossicles, tympanic membrane, basilar membrane, oval and round windows) and fluid media (air in the ear canal and middle ear, brain and cochlear fluid). For the acoustic application considered here, it is legitimate to make the assumption of small deformations and to adopt the laws of isotropic linear elasticity for solid media and the Helmholtz equation for fluid media. However, local variations in density and elasticity of materials as well as viscoelastic behavior could be considered (e.g. [15]). Measuring the *in vivo* mechanical properties of biological materials is a very difficult task. Most of the time, measurements can only be done *in vitro*. In addition, the environmental conditions of experimental equipment (i.e. humidity and temperature) may affect the mechanical properties of the tissues. Particularly with the ear components (ear canal skin, eardrum, middle ear, etc), experimental measurements of the mechanical properties *in vitro* are very limited due to small size of the components. Thus, the available mechanical properties have large uncertainties. Therefore, the mechanical properties of the FE model materials should be considered as random variables. The average properties of the biological materials of interest will be taken from the most recent literature (e.g. [16,17]) and the VM will be calibrated and validated using statistical approaches. Regarding the ear canal skin which is a very important component for hearing protection because of the coupling mechanisms with the HPD, a special model will be developed in parallel in collaboration with researchers from Sheffield University and the parameters of the behavioral law will be determined using appropriate characterization methods [18].

2.1.3. VM of the head coupled to a custom molded earplug

The geometries of the head (supposedly fixed at its base) and a custom molded earplug of known properties (silicone) will be imported and appropriately meshed in a FE commercial software dedicated to the problems of fluid-structure interaction (COMSOL Multiphysics (© COMSOL) or Simcenter 3D (© Siemens)). The acoustic interaction between the infinite external fluid surrounding the head will be taken into account by a PML (Perfectly Matched Layer). The associated elasto-acoustic problem will be solved in the frequency domain [20Hz-8kHz] which is the one conventionally used for hearing protection. The sound pressure inside the ear canal will be calculated for an acoustic and structure borne excitations.

2.1.4. Calibration and validation of the VM with respect to an EAP

The VM of the head coupled to the custom molded earplug will be calibrated and validated step by step by fabricating associated accurate experimental anatomical phantoms (EAP) with increasing complexities (e.g. empty skull, empty skull + brain, ..., empty skull+outer ear, …, complete head with hearing system) with the support of a specialized company. Figure 3 displays an example of outer ear experimental phantom fabricated from MRI images of a human subject [14]. A particular challenge lies in the fabrication of the tympanic membrane, middle ear and internal ear. However, the manufacturing of these very small elements may not be necessary. For an acoustic excitation, a custom made electroacoustic coupler allowing for mimicking the subject eardrum acoustic impedance will be designed. For bone conducted excitation, depending on the degree of realism sought, it may be necessary to account mechanically for the middle and inner ear part. An artificial tympanic membrane coupled to an acousto-mechanical circuit representing the vibroacoustic effect of the middle and inner ear may be needed. The recent advances in terms of 3D printing for middle ear [19] and fabrication of artificial tympanic membrane [20] will be also considered nonetheless. At this stage, the geometry of each VM is considered as deterministic since it was constructed with high precision. The calibration will be carried out on materials parameters. This implies that the calibrated input parameters will be valid only for the corresponding VM FE model. For each of these EAP, synthetic polymeric materials with mean properties similar to those collected in section 2.1.2 will be used. These materials will be characterized in laboratory using classical techniques (e.g. DMA) to provide initial input calibration parameters including the related uncertainties to the FE model. The EAP will be instrumented with various sensors (accelerometers, hydrophones, microphones, thermocouples) and a heating element to maintain the temperature of the ear canal at 37ºC. For each EAP, the corresponding VM will be statistically calibrated and validated by comparing the predicted vibroacoustic response with that measured using for example the approach described in [17]. Both open and occluded ear measurements will be carried out for an acoustic and a mechanical excitation. Insertion of the earplug and acoustic leaks will be controlled.

Figure 3. Example of outer ear experimental phantom fabricated from polymeric materials (© True Phantom)

2.1.5. Calibration of the VM with respect to the human subject

The properties of the tissues materials used in the previous steps do not correspond to those of the scanned human subject. The previous step made it possible to have confidence in the VM of the complete head coupled to a custom molded earplug of known properties. This VM will be statistically calibrated and validated using experimental data collected on the human subject whose head has been scanned using the same approach as described in section 2.1.4. Ultimately a final EAP with corresponding calibrated properties will be manufactured.

2.2. Improvement of HPDs VM

As mentioned in the introduction, several HPDs numerical VMs have been developed in the past but they suffer from various limitations and need to be improved. In this section, details are given about the various improvements that are addressed in this research. Note that all the HPDs FE VM will be first calibrated and validated based on comparisons between simulation results and experimental data carried out on a GRAS CB-45® (GRAS Sound & Vibration, Denmark) artificial test fixture including simplified circular cross section cylindrical ear canals with a silicone artificial skin ring.

2.2.1. Earplug VM

Several earplug FE models (silicone custom molded and foam earplugs) have been proposed in the past by the authors (e.g. [3,11]). In this research, FE models will be improved by taking into account more complicated earplug shapes, a more realistic outer ear geometry, more adequate behavioral laws for roll down earplugs and the effect of the ear canal/earplug deformation. Other types of earplugs (roll down, premolded and push-to-fit) than those studied previously (see Fig.4) will be scanned in their undeformed state from 3D digitization systems available at ÉTS and the associated mechanical properties will be characterized in the ICAR laboratory at ÉTS.

Obtaining the earplug geometry once inserted in the ear canal and thereby evaluating the possible acoustic leaks and deformation state is a real challenge. Medical imaging techniques such as MRI and CT-scans are promising. Preliminary attempts to detect the shape of several kinds of earplugs inserted in real or synthetic simplified ear canals using these techniques have been carried out. MRI images allow one to clearly see silicone custom molded earplugs. Ultra-fit earplugs are also visible but the IRM poor resolution makes it difficult to perform a segmentation. Other earplugs containing foam components (classic or pushin earplugs) cannot be seen. When using CT-scan images, most of the tested earplugs can be clearly seen (silicone and acrylic custom molded, molded Ultrafit). The foam-based earplugs contours are still visible but less clearly because of the weak density contrast between the earplug and air contained in the ear canal.

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

Figure 4. Example of earplugs considered in this study ((a) roll down (foam), (b) premolded (Ultrafit), (c) push-to-fit (d) custom-molded)

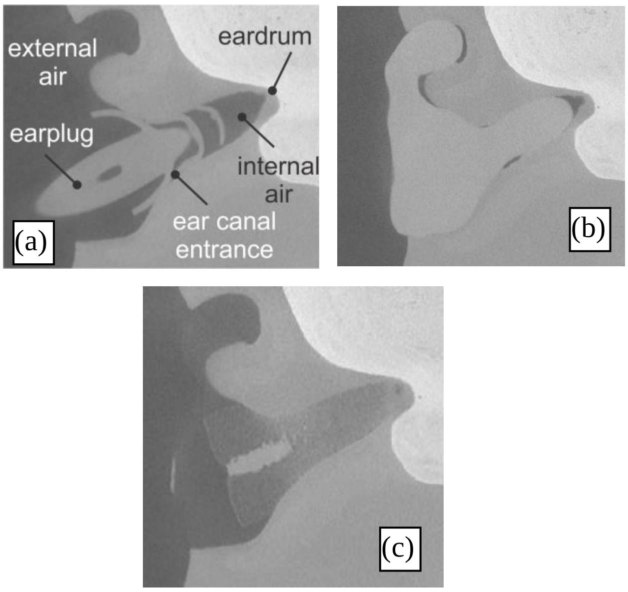

Figure 5. Example of micro-CT scan images of deformed earplugs in an artificial ear phantom ((a) Ultra-fit ©3M, (b) silicone custom molded ©Laboratoire Laviolette, (c) roll down foam ©3M)

Figure 5 displays examples of CT-scan images of deformed earplugs inserted in a human-like artificial ear. Another challenge is to take into account in the VM the spatial inhomogeneity of moldable earplugs mechanical properties since the earplug is submitted to different radial compression rates depending on the part of the ear canal it is in contact with. Again, CT-scan images are helpful here since compressed zones for foam earplugs can be identified. This requires carrying out appropriate mechanical characterization of the earplug material for various radial compression rates. An inverse approach based on transfer matrices in an impedance tube is currently being developed by the research team to obtain such mechanical properties [21,22].

2.2.2. Earmuff VM

For earmuffs, a new behavioral model for the cushion of commercial earmuffs, of viscoelastic orthotropic equivalent solid type [23] or multi-domain type (rubber sheath, comfort foam, air) and integrating the spatial nonuniformity of compression will be developed. This rises the question of characterization of the corresponding mechanical properties (orthotropic equivalent solid cushion) and coupling conditions between each component (multidomain cushion model). A better representation of the mechanical coupling between the components of the earmuff (e.g. backplate and cushion) will be studied. The internal absorbent foam will be taken into account by a suitable model and the influence of the foam-earmuff interface conditions will be analyzed.

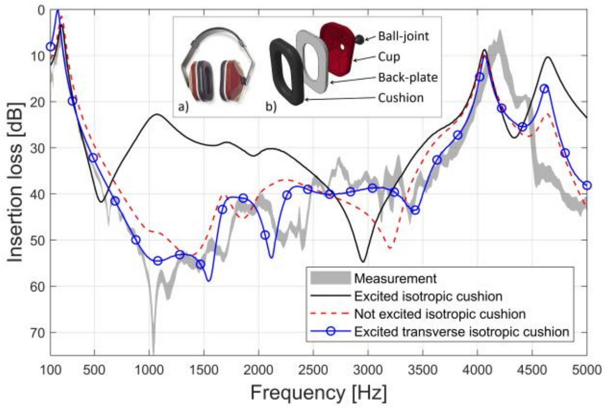

Figure 6. Impact of the comfort cushion modeling on the simulated IL of a commercial earmuff EAR1000- comparison with measured IL (taken from [23])

An example of improvement of a commercial earmuff (EAR-1000 ©3M) FE model is presented in Figure 6. This figure shows the benefit of using a transverse isotropic equivalent solid (ES) mode for the cushion over an isotropic model [23]. Predicted and measured sound attenuations (insertion loss (IL)) of an earmuff (Figure 6, a) in a simplified configuration (the earmuff rests on a rigid baffle and the foam pad inside the cup is removed (Figure 6, b)) are compared for several cushion modelings. Indeed past works have shown that the IL at medium frequencies is particularly sensitive to the way the cushion is modeled. Three alternative modeling of this one are investigated: isotropic ES whose external lateral walls are either (i) excited acoustically (solid black line) or (ii) not excited (dashed red line) and (iii) transverse isotropic ES whose external lateral walls are excited acoustically (solid blue line with circles). While measured IL (gray zone) is largely underestimated by the excited isotropic cushion model due to a parasitic transverse mode of the cushion, excluding the acoustic excitation of the lateral walls of the isotropic cushion improves the predicted IL even if this hypothesis is debatable physically [23]. On the other hand, the excited transverse isotropic ES model provides better agreement between simulation and measurement because the parasitic cushion mode is shifted to higher frequencies.

2.2.3. Dual protection VM

For dual protection (DP) systems, most published studies have focused on the attenuation measurement rather than numerical modeling however they lacked well-designed methodologies to clearly understand the sound transmission mechanisms through the whole system and to characterize the real coupling conditions between different components. For DP systems, there aren’t any satisfactory prediction models at the time being. In this research VM of DP/ear canal systems based on the combination of earplugs and earmuff VMs described in sections 2.2.1 and 2.2.2 and relying on a thorough experimental analysis of sound transmission paths through the system will be developed.

2.3. Evaluation and exploitation of the VM of the head coupled to a variety of HPDs

The FE VM of the head coupled to a custom molded earplug will be used to analyze mechanisms of sound transmission through the system via sensitivity analyzes. Once statistically calibrated and validated, the FE VM of the head will be evaluated for various HPDS like other types of earplugs than the one used for calibration and for earmuffs and dual protection. The FE models of these HPDs will have been obtained in section 2.2. The simulation results will be compared with measurements on the human subject. The VM of the head coupled to the various PAs studied will be exploited by performing sensitivity analyzes on the model parameters (e.g. physical properties and insertion depth of earplugs, presence of acoustic leaks, ...) in order to quantify their impact on the sound pressure at eardrum and better understand the mechanisms of sound transmission through the head/HPD system.

3. Conclusion

This research aims ultimately at developing computational tools and test benches to help design various effective and comfortable HPDs adapted to the people who wear them and to the sound environment in which they evolve. This paper focuses on acoustical comfort and is interested in predicting the frequency dependent vibroacoustic response of an HPD coupled to a human head. The methodology to develop a unique and realistic numerical VM in the audible frequency range of an *in vivo* human head wearing an HPD together with an associated instrumented Experimental Anatomical Phantom (EAP) is described. Preliminary results regarding the assessment of the deformation of an ear canal induced by the insertion of an earplug, the deformed shape of earplugs and the evaluation of an improved earmuff FE VM and have been presented.

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