Paper presented at e-Forum Acusticum 2020
Online, Dec. 07-11, 2020

Numerical Modeling of the Vibro-Acoustic Behavior of an Artificial Ear Dedicated to the Study of Hearing Protectors

S. Benacchio[1] **F. Sgard[2]** **O. Doutres[1]**

[1] École de Technologie Supérieure, 1100 Rue Notre-Dame Ouest, Montréal, QC, Canada H3C 1K3

[2] Institut de Recherche Robert Sauvé en Santé Sécurité du Travail, 505 Boulevard de Maisonneuve O., Montréal, QC, Canada H3A 3C2

Franck.Sgard@irsst.qc.ca

ABSTRACT

Hearing protection devices like earplugs are largely used to protect workers against noise. The discomfort related to the use of earplugs is known to reduce their effectiveness. Since this discomfort remains difficult to evaluate, it seems necessary to improve current tools like acoustical test fixtures to help earplug manufacturers to design more comfortable devices. In this perspective, a numerical model of an artificial ear based on the finite element method is proposed. This model aims to investigate the important features needed to correctly evaluate objective indicators related to the acoustical comfort of earplugs using an artificial ear. In the present preliminary study, the ability of this numerical model to simulate the insertion loss of earplugs is tested by comparing sound pressure level transfer functions computed in both the open and occluded numerical earcanal with experimental data measured on the corresponding physical artificial ear. Results reveal that the proposed numerical model simulates well the sound pressure level in an open earcanal but fails in the occluded case above 400 Hz. Possible sources of discrepancies are investigated. In particular, the effect of various model parameters on the acoustic response in the earcanal is evaluated.

1. INTRODUCTION

In noisy workplace environments, a widespread solution to protect workers against hearing loss is the use of hearing protection devices (HPDs) such as earplugs. However, the discomfort associated with these HPDs limits their wearing time and therefore their effectiveness [1]. This discomfort remains difficult to assess using measurable quantities which would help manufacturers and users to respectively design and choose effective and comfortable HPDs. In the case of acoustical discomforts due to earplugs, such as difficulty in communicating and hearing useful sounds or occlusion effect, the sound pressure at the eardrum is a good candidate to objectively evaluate HPDs acoustical comfort. To avoid cumbersome studies involving a large panel of participants, acoustical test fixtures (ATFs) can be used to assess HPD attenuation by measuring the sound pressure in the earcanal [2]. However, current ATFs are not realistic enough to properly reproduce every acoustical or mechanical propagation paths through the ear/HPD system. For example, they generally do not properly account for (i) inter- and intra-variability in earplug positioning mainly due to the complex geometry of real earcanal shape (even though very recent ATF may include realistic shaped earcanal) and (ii) a realistic transmission of mechanical vibrations responsible for the occlusion effect since they do not include a bony nor a cartilaginous part. Thus, it seems necessary to improve current ATFs to better evaluate the acoustical pressure in the earcanal when earplugs are used. In this perspective, this study focuses on the development of numerical models based on the finite element method and dedicated to the study of one objective indicator related to the acoustical dimension of earplug comfort: the insertion loss (IL). Transfer functions using the sound pressure levels needed to simulate this indicator are compared with experimental results obtained on a realistic artificial ear to evaluate the model. The difficulties and perspectives related to the use of this model to accurately reproduce the sound propagation through an ear/HPD system are discussed.

2. NUMERICAL AND EXPERIMENTAL ARTIFICIAL EAR

2.1 Realistic geometry

In order to design an artificial ear dedicated to the study of the IL of earplugs, a 3 dimensional (3D) numerical reconstruction of a human ear was designed from magnetic resonance images obtained on a living subject [3]. The ear geometry was reconstructed using two different domains corresponding to bony part and soft tissues (fat, muscles, skin and cartilage) and is depicted in Figure 1(a).

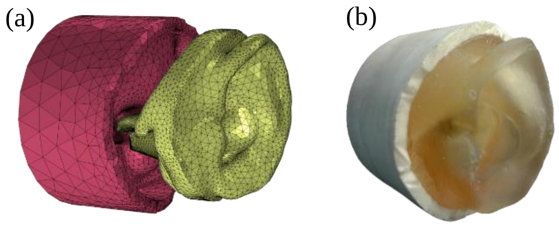

Figure 1. (a) 3D numerical reconstruction used to design the FE model and (b) the experimental artificial ear. Colors on the 3D numerical reconstruction correspond to the bony part (red) and soft tissues (yellow).

For practical reasons, this 3D numerical reconstruction was embedded in a rigid cylinder with an 8 cm diameter. For the sake of simplicity and as a rough first approximation, the end of the earcanal was considered as rigid instead of using an impedance mimicking the acoustical effect of the middle and inner ear.

2.2 Experimental artificial ear, special earplug and material properties

The experimental artificial ear corresponding to the aforementioned 3D reconstruction was fabricated using two synthetic materials mimicking the hardness of human bone and soft tissues and is represented in Figure 1(b). Once fabricated, the properties (density, Young's modulus, Poisson's ratio and loss factor) of these materials were experimentally measured when possible to be used in the FE model presented in Section 2.3 (see Table 1).

In order to occlude the artificial earcanal, a special earplug was designed to ensure at the same time (i) an easy positioning inside the earcanal of the artificial ear and (ii) a good sound attenuation. Regarding the first point, the shape of the earplug corresponds to the geometry of the earcanal from the concha to the second bend. The base of the concha is used as a reference to place the earplug in the earcanal in a reproducible manner. Regarding the second point, a 5 mm length of the inner tip of this earplug is radially dilated by 1 mm to create an efficient acoustic seal inside the earcanal. The earplug was 3D-printed using a rigid resin whose properties are given in Table 1.

2.3 Finite element modeling

The finite element (FE) model corresponding to the aforementioned artificial ear has been developed using Comsol Multiphysics (Comsol Inc., Burlington, Massachusetts, USA). The ear and earplug geometries were imported and meshed using quadratic tetrahedron elements with a resolution of at least 6 and 2 elements per wavelength for acoustic and solid domains respectively. Note that**,** even though the element number criterion for solid domains looks small, a convergence study has shown that it is sufficient to achieve convergence of the solution. The properties of the domains (bone, soft tissues and earplug) used in the FE model are experimentally identified (see Section 2.2) or found in the literature and are given in Table 1.

Material	Density [kg.m^{-3}]	Young's modulus [kPa]	Poisson's ratio [ ]	Damping factor [ ]
Bone	2267	13.6e6	*0.31* [4]	*0.1* [5]
Soft tissues	1007	284	0.28	0.045
Earplug	1180	*2.8e6* [1]	*0.35*	*0.284*

Table 1. Properties of the materials used in the FE model and to fabricate the experimental artificial ear. Values derived from literature and experimentally identified are respectively indicated with italic and regular lettering.

Since Poisson's ratio and damping factor of the earplug material were not found in the literature, typical values from the Comsol material library were used.

The artificial ear was assumed to be immersed in an infinite air domain in which an acoustic point source was located. To simulate this free field configuration, the artificial ear model was embedded in a spherical air domain coupled to a perfectly matched layer with 7 elements within its thickness. The artificial ear was assumed to be mechanically free and a fluid-structure coupling condition was applied between the air and the materials of the artificial ear. The coupling condition between the earplug and the soft tissues of the artificial ear can vary and is discussed in Section 3.

2.4 Sound pressure level transfer functions in the open and occluded earcanal

The insertion loss due to the earplug inserted in the earcanal depends on the acoustic pressure at the tympanic membrane location when the earcanal was opened (p_{open}) and occluded by the earplug ($p_{occluded}$) and reads

$$\boldsymbol{IL = 20\log_{10}\left(\frac{|p_{open}|}{p_{ref}}\right) - 20\log_{10}\left(\frac{|p_{occluded}|}{p_{ref}}\right)},$$

with p_{ref} = 20e^{-6} Pa and |.| indicates the absolute value.

Thus, the FE model must correctly simulate the pressure inside the earcanal when the latter is open and occluded. In the next section, the transfer functions between the pressure in the earcanal $p_{earcanal}$ and the pressure p_0 measured at the same point but without the artificial ear are investigated for the open and occluded cases. Simulations are compared with experimental results obtained using a microphone located at the inner extremity of the experimental artificial earcanal. Measurements were performed in an anechoic chamber where the artificial ear was hung using bungees to simulate the free boundary conditions. The acoustical source was a white noise generated using a Q-MHF monopole volume acceleration source (Siemens, Munich, Germany) located 20 centimeter in front of the artificial ear.

3. RESULTS AND DISCUSSION

Figure 2 presents the comparison between measured and simulated narrow band sound pressure level transfer functions for the open and occluded earcanal.

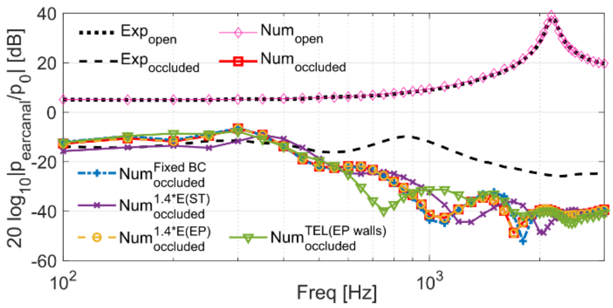

Figure 2. Measured (black curves) and simulated (colored curves) sound pressure level transfer functions for open (dotted and magenta) and occluded (dashed and red) case. Blue, purple, yellow and green curves correspond respectively to simulation (1), (2), (3) and (4) (see below).

For open earcanal, the FE results fit very well with experimental data. For occluded earcanal, the simulation results are close to the experimental data up to 400 Hz.

[1] https://archive-media.formlabs.com/upload/XL-DataSheet.pdf (last viewed 2020/10/28)

After this limit, the simulated sound level in the occluded earcanal is much lower than the measured one. The reasons of these discrepancies attributed to the FE model are: (a) boundary conditions, (b) material properties (ear tissues and earplug) and (c) coupling condition between the earplug and the soft tissues. To test the effect of these potential sources of discrepancies, other simulations were conducted (1) fixing three points at the back of the artificial ear model ($Num_{occluded}^{Fixed\ BC}$), (2) increasing by 40% the Young's Modulus of soft tissues ($Num_{occluded}^{1.4*E(ST)}$), (3) increasing by 40% the Young's Modulus of the earplug ($Num_{occluded}^{1.4*E(EP)}$) and (4) adding a thin elastic layer at the boundary surface between earplug and soft tissues mimicking the lubricant used during measurements ($Num_{occluded}^{TEL(EP\ walls)}$).

It can be shown on Figure 2 that the modifications of boundary condition (blue curve) and Young's modulus of the earplug (yellow curve) do not change significantly the results. The Young's modulus of the soft tissues (purple curve) and the contact condition between the earplug and the soft tissues (green curve) have a greater effect on the results. The fact that the soft tissues Young's modulus has an effect on the results is not surprising since the compression of the tissues around the tip of the earplug is not taken into account in the simulation. The effect of the coupling condition between the earplug and soft tissues is difficult to evaluate but might also have a part of responsibility in the bad fitting of simulations with measurements. It is also noteworthy that other sources of discrepancies were not considered in this study. For example, the presence of acoustic leaks or a poor self-insertion loss of the physical artificial ear should be further numerically investigated to improve the quality of the model.

4. CONCLUSION

In the perspective to develop tools dedicated to the study of earplugs insertion loss, an artificial ear model based on the finite element method has been developed. This model has a realistic geometry and mimics the bony part and soft tissues surrounding the earcanal. To evaluate the ability of this model to correctly simulate earplug insertion loss, sound pressure level transfer functions for the open and occluded earcanal have been computed and compared to experimental data measured on the corresponding physical artificial ear. Results show that the open case is well simulated by the model but not the occluded case above 400 Hz. Several possible sources of discrepancies were numerically tested to investigate their effect on the sound pressure level inside the occluded earcanal. The material properties of the soft tissues and the coupling condition between the earplug and the earcanal walls seem to be factors to work on to improve the numerical model.

5. REFERENCES

[1] O. Doutres, F. Sgard, J. Terroir, N. Perrin, C. Jolly, C. Gauvin, and A. Negrini: "A critical review of the literature on comfort of hearing protection devices: definition of comfort and identification of its main attributes for earplug types," *International Journal of Audiology*, Vol. 58, No 12, pp. 824-833, 2019.

[2] E. Berger: "Preferred methods for measuring hearing protector attenuation," *Proceedings of the 2005 Inter-noise Congress*, pp. 1-10, 2005.

[3] S. Benacchio, O. Doutres, A. Le Troter, A. Varoquaux, E. Wagnac, V. Callot, F. Sgard: "Estimation of the ear canal displacement field due to in-ear device insertion using a registration method on a human-like artificial ear," *Hearing Research*, 365. Pp. 16-27, 2018.

[4] Abid, A., Pereira, D., Fernandes, J. C. et Belanger, P. (2017). Sensitivity study of ultrasonic guided waves to cortical bone mechanical properties with axial and circumferential propagation. *Acta Acustica united with Acustica, 103*(3), 421-429.

[5] Brummund, M. K., Sgard, F., Petit, Y. et Laville, F. (2014). Three-dimensional finite element modeling of the human external ear: simulation study of the bone conduction occlusion effect. *Journal of Acoustical Society of America, 135*(3), 1433–1444.