Development of a Simplified Axi-Symmetric Finite Element Model of the Auditory Canal Occluded by an Earplug: Variability of the Attenuation as a Function of the Input Parameters

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1. INTRODUCTION AND OBJECTIVES

In Quebec, 500 000 workers are confronted to the problem of noisy work environment [1]. A common solution to prevent the problem of hearing loss due to noise exposure consists in using hearing protection devices (HPD's), like earplugs (EP) or earmuffs. In practice, EP are often uncomfortable and/or do not always perform as desired [2]. The present study deals with the development and the use of an axi-symmetric finite element model (FEM) of the ear canal (EC) occluded by a silicon EP. This model is used to determine how the input parameters influenced the attenuation, in order to improve it.

The first step of this study is to implement and to validate the simplified axi-symmetric model with the help of the paper [3] and to extend this model for a more realistic boundary condition for the EP. The second step consists in using indirectly the FEM model to perform a global sensitivity analysis and to determine Sobol indices. These indices give the information about how the variation of the output of a physical system is influenced by the variation of the input parameters. Unfortunately, applying directly these tests on the FEM model is cumbersome because they require a huge number of computations. The FEM EP/EC model is used here to determine a meta-model, as a combination of a polynomial regression of the response given by the FEM EP/EC model, obtained by a complete design of experiments and corrected by the most probable residual function. Two different meta-models are built. The first one is a function of the mechanical parameters of the EP (Young's modulus, Poisson ratio and density) and the second one is a function of the geometrical parameters of the EP (length and radius). Once the meta-models are validated with the EC/EP FEM for a new set of parameters (mechanical or geometrical), the statistical tests are applied to the meta-models that give instantaneously the predicted attenuation values.

2. METHODOLOGY

2.1 Modeling the EP/EC system

Based on the axi-symmetric assumption [4], a recent study [3] showed the feasibility of the FEM to predict the attenuation of a silicon cylindrical earplug, with fixed boundary conditions, inserted in a cylindrical EC. Here, the EP is also considered as a solid cylinder inserted into a cylindrical EC, modeled as an air cavity. This system is

terminated by a tympanic membrane (TM) which is supposed to act as a locally reacting boundary impedance condition (impedance values of the IEC711 artificial ear). In real life, the EC is constituted by a complex assembly of skin, soft tissues and bone parts. An innovative alternative is used here to take into account the coupling between the EP and the EC. This coupling (calculated with the help of an axi-symmetric model including skin, soft tissues and bone parts) is applied as a mechanical impedance on the lateral walls of the EP. This fluid/structure problem is solved using the FEM to calculate the displacement field in the EP and the acoustic pressure in the remaining domain of the EC. The noise reduction (NR_0) indicator is used to characterize the attenuation of the EP, i.e. the transfer function between the acoustic pressure at the center of the tympanic membrane and the incident one:

$$NR_0 = 20LOG_{10}\left(\frac{|P_{TM}|}{|P_{incident}|}\right) \qquad (1)$$

2.2 Global sensitivity analysis

The meta-models (one for each set of parameters) are constructed to approximate the output NR_0 of the FEM model:

$$NR_0 \cong \widehat{NR_0} = G(x_i) + Z(r_k) \qquad (2)$$

The $G(xi)$ term in (2) is a multi-linear regression of the output based on a complete design of experiments with three different levels for each parameters xi. All the values used for the design of experiments, are reported in table 1. In both cases, the aim is to determine the polynomial coefficients relative to each parameter and their interaction. The $Z(rk)$ term in (2) is a correction factor of the multi linear regression using the known residual values between and NR_0 and $\widehat{NR_0}$.

Table 1: Values of the parameters of the EP used to compute the twice meta-model.

Code level	E (Mpa)	ρ (kg/m³)	v	L (mm)	R (mm)
-1	7.5	850	0.44	**12.5**	**3.75**
0	**8.5**	**1000**	0.46	15	4.75
1	9.5	1150	**0.48**	17.5	5.75

The bold values correspond to the ones used in [3]. The approximate polynomial function allows to obtain the instantaneous calculation of the response for a new set of parameters inside the [-1;1] domain.
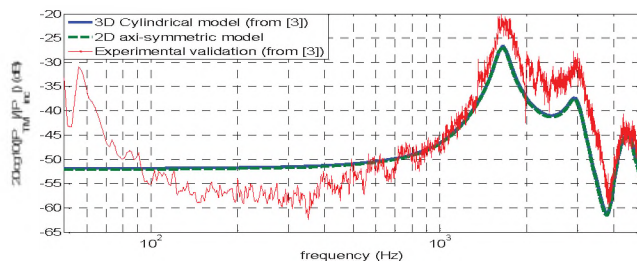
3. RESULTS AND DISCUSSION

Figure 1: Validation of the axi-symmetric model with the help of [4], for fixed boundary condition
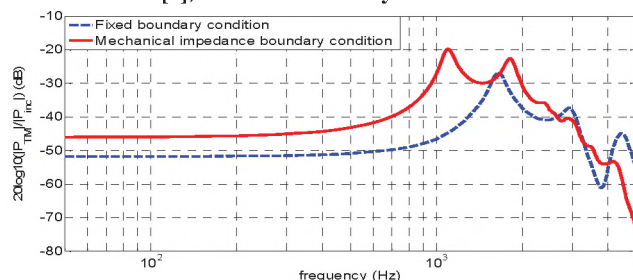

Figure 2 : Influence of the boundary condition applied to the lateral walls of the EP
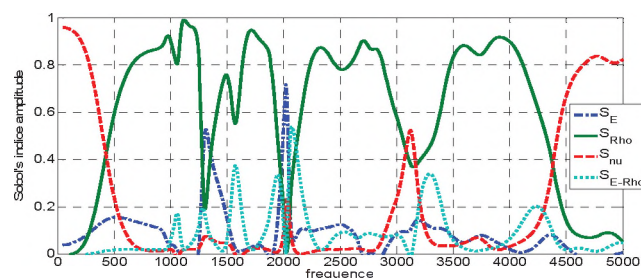

Figure 3 : Sobol indices calculated with the first meta-model (mechanical parameters)
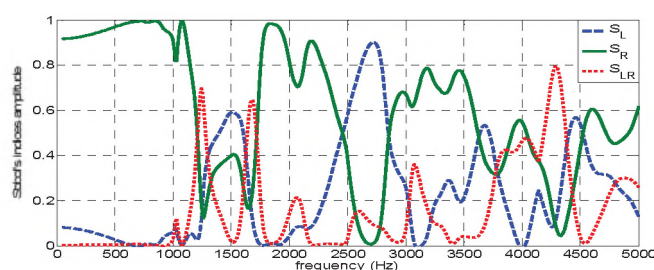

Figure 4 : Sobol indices calculated with the second meta-model (geometrical parameters)

Figure 1 indicates good agreement between the curve obtained by [3] (cylindrical 3D model) and those obtained here (2D axi-sym). The third curve corresponds to an experimental validation, realized in the study [3]. Between 400 Hz up to 5000 Hz, the axi-sym model matches the experiment data. The difference between the model and the experimental data is explained by the author [3] due to a small leakage on the coupler. The peaks observed in figure 1 correspond to particular vibration modes of the plug. A modal analysis on the «in vacuo» structure allows finding the frequency of these vibration modes together with their mode shapes.

Figure 2 shows the modification of the NR_0 indicator for a more realistic boundary condition. The vibration modes of the structure were influenced by the boundary conditions and by applying a mechanical impedance to the laterals walls of the EP are able to move. This result shows that it is not enough to take a fixed boundary condition to predict correctly the attenuation of an EP inserted in the EC. Even for a simplified numerical model, the coupling between the EC and the EP are to be taken into account.

Figure 3 indicates that the variation of the system rigidity (Young modulus and Poisson ratio) strongly influences the variation of the attenuation in low frequencies (up to 500 Hz). In the rest of the frequency domain, the variation of the density, the Young modulus and their interaction influence the attenuation on the whole frequency band (approximately 80% of the variation of the attenuation). In this frequency domain (500 Hz to 5000 Hz), it is important to control the density of the EP as it is the factor that mostly influences the variation of the attenuation.

Figure 4 indicates that the radius influenced the variation of the attenuation more than the length. Up to the first resonance of the system (1200 Hz), and between each resonance, the variation of the radius counts for more than 80% of the variation of the attenuation. For the first two resonances (1200 Hz and 2700 Hz), the variation of the length and the length/radius interactions act locally for 60% of the variation of the attenuation.

Finally, the obtained models could be used to determine the best set of parameters that will improve the attenuation of the EP. This method could be extended to other types of EP.

REFERENCES

[1]   J.P. Vigneault, "Pour un meilleur support de la recherche au plan d'action 2006-2008 du réseau de santé publique en santé au travail," *La recherche sur le bruit en milieu de travail*, IRSST, Éd., IRSST: 2007.

[2]   E.H. Berger, L.H. Royster, et D.P. Driscoll, *The noise manual*, AIHA Press, 2003.

[3]   F. Sgard, H. Nélisse, M. Gaudreau, J. Boutin, J. Voix, et F. Laville, *Étude de la transmission sonore à travers les protecteurs auditifs et application d'une méthode pour évaluer leur efficacité effective en milieu de travail - Partie 2 : Étude préliminaire d'une modélisation des protecteurs auditifs par éléments finis*, 2010.

[4]   M.R. Stinson et B.W. Lawton, "Specification of the geometry of the human ear canal for the prediction of sound-pressure level distribution," *The Journal of the Acoustical Society of America*, vol. 85, Juin. 1989, p. 2492-2503.