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A 2D Axisymmetric Finite Element Model To Assess The Contribution Of In-Ear Hearing Protection Devices To The Objective Occlusion Effect

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ABSTRACT

The use of in-ear devices such as hearing aids or earplugs can be accompanied by an amplification of physiological noises upon their insertion in the earcanal, also called occlusion effect. Classical lumped elements-based prediction models for the occlusion effect consider the source of this effect solely due to the ear canal walls vibration. In most of these models, the in-ear device is considered as a simple infinite acoustic impedance which modifies the ear canal cavity length and thereby the ear canal walls vibrating surface depending on the insertion depth. The contribution of the earplug sound radiation to the occlusion effect is not considered as a significant mechanism. However, some authors have recently demonstrated using a finite element (FE) model that the earplug affect the vibration pattern of the ear canal walls but also may play the role of sound source in the unobstructed ear canal cavity thereby affecting the occlusion effect. In the most sophisticated lumped models, the in-ear device acts additionally as a loading on the ear canal wall which in turn modifies the ear canal free walls vibration. However the skin/in-ear device mechanical coupling is simplified and the earcanal cavity/in-ear device vibroacoustic coupling is ignored. Other physical effects such as leaks between in-ear device and skin may affect the occlusion effect at low frequencies but this has been rarely tackled in the literature. In this paper, a 2D axisymmetric FE model of the human open and occluded external ear including or not the presence of leaks is proposed to calculate the occlusion effect induced by earplugs. This model is used to study the influence on the occlusion effect of the various couplings skin/earplug/earcanal cavity for various insertion depths and leak diameters.

Keywords: Occlusion effect, Hearing protection devices, finite element modeling
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1. INTRODUCTION

The use of in-ear devices such as hearing aids or earplugs can be accompanied by an amplification of physiological noises (e.g one's own voice, chewing, heart beat etc.) upon their insertion in the earcanal, also called occlusion effect (OE). This effect is perceived as an increase of the sound amplitude at low frequency subsequent to the blocking of the earcanal by the in-ear device. It can be quantified objectively by applying to the subject a bone conduction stimulation (for example a mechanical transducer on his/her skull) or a mixed air/bone conduction stimulation like one's own voice and evaluating the difference of sound pressure level measured at the eardrum when the ear is occluded by the in-ear device and when it is open. Fundamentally, at low frequency and for an acoustically rigid occlusion, the OE is explained by the earcanal impedance increase due to the occlusion [1,2]. Thus, for a given earcanal wall vibration, the pressure generated by the earcanal wall increases in the occluded case compared to the open one [1,2]. However, several factors are known to influence the OE [1,3–8]: (i) the ear anatomy (geometry and properties of the tissues surrounding the earcanal), (ii) the position and nature of the stimulation and (iii) the occlusion device, namely its type, its fit and its location in the earcanal.

Although several studies mentioned the importance of the aforementioned third factor, to the authors' knowledge, few authors have evaluated the contribution of the occlusion device to the sound pressure level (SPL) in the occluded earcanal. Lee [5] carried out an experimental study to examine the effect of the earplug type for two insertion depths (shallow and deep) on the occlusion effect magnitude. Statistically significant effects of the earplug mechanical properties on the occlusion effect were observed for deep insertion but not for shallow insertion. Hansen [4,9] carried out occlusion effect experimental measurements on human subjects using a continuous speech, nasal sound and chewing stimulation to examine the influence of mechanical properties of earmoulds using both custom acrylic earmoulds and foam earplugs for medium insertion depth. He concluded that both the mass and the elasticity of the occlusion device influence the occlusion effect, the occlusion effect being larger when its stiffness and/or mass increase. From a modeling point of view, the OE is commonly calculated using lumped elements models either based on a bone conduction excitation [1] or a combined air/bone-conduction stimulation [4,8] possibly accounting for leakages [4,8]. These models consider the source of this effect solely due to the earcanal walls vibration, thus neglecting the possible contribution of the inner earplug surface vibration. Most of the time, the in-ear device then acts as an acoustically rigid blocking device that simply reduces the length of the unobstructed earcanal cavity and thereby the portion of earcanal walls area radiating in the earcanal cavity [4,8]. However, it is acknowledged that reducing the in-ear device to an infinite acoustic impedance is a simplification, and the incorporation in these models of a more complex acoustic loading impedance and inertial effects from the occlusion devices would probably be more realistic [1]. In this perspective, Hansen proposed a mathematical model to predict the OE using one's own voice as sound source [4]. In his lumped element model, the earplug was considered as an acoustically rigid body subjected to elastic boundary conditions induced by the surrounding earcanal tissues. The source of vibration was assumed to be the earcanal walls, the occlusion device playing the role of a mechanical load acting on the tissues but not radiating into the occluded earcanal cavity for the chosen insertion depth. Note that only standard insertion depth was considered for both occlusion devices (about 8 to 13mm). The author claims that this model is capable of estimating the measured OE difference between the acrylic earmould and the foam earplug. He also included in his model the effect of leakage between the occlusion device and the earcanal using equivalent visco-thermal tube and slit acoustic impedances. He concluded that for a voice excitation, the OE can increase or decrease at low frequency depending on the dimensions of the leakage compared to the case with no leakage. In addition, he found that accounting for leakage using a slit shape allows simulation results to better agree with experimental results. More recently, finite element (FE) models of the occlusion effect have been developed to help examine some assumptions made in lumped models and further improve the understanding of the occlusion effect mechanisms. Brummund [6] considered a 2D axisymmetric FE model of the unoccluded and occluded outer ear to predict the occlusion effect of both silicone and foam earplugs for various insertion depths. He showed that while the earplug contributes to the occlusion effect at deep occlusion (occlusion down to the bony meatus) it is of little importance at shallow earplug insertion. This confirms Lee's experimental results [5]. For a deep insertion (the cartilaginous part of the earcanal is almost entirely covered by the earplug), the inner earplug surface is shown to contribute more to the SPL in the occluded earcanal than earcanal walls in contact with the air cavity for both earplug types. For shallow insertion, the earcanal walls in contact with the air cavity are the most important contributor to the SPL in the occluded earcanal. Note that the contribution of the earplug sound radiation in the earcanal cavity has been eliminated as a possible explanation of the OE by Hansen [4] probably because he has not considered a deep insertion in his experimental data with acrylic mould and foam earplug. Using a similar FE model, Brummund [7] examined also the role of earplug leaks in combination with incoherent airborne and structure borne excitation for a silicone earplug and a medium insertion depth. Leaks were accounted for in the model as an equivalent cylinder centered on the earplug symmetry axis and containing a visco-thermal fluid. The presence of both small leaks and airborne noise caused the simulated OE to increase at low frequency (with respect to airborne noise). The frequency at which maximum increase in OE occurred was influenced by the resonance frequency of the system earplug leak / earcanal which form a Helmholtz resonator like structure. This confirms Hansen's results.

The literature review shows that the underlying physical mechanisms of the in-ear device contribution to the OE depend on its insertion depth. For the lumped element models, the in-ear device sound radiation in the earcanal cavity is not a contributing factor to the OE whereas it is for the more recent numerical models when the occlusion device is deeply inserted. In addition, the effect of leakage between the earplug and the skin on the OE has been investigated using either (ii) a simplified model for both the leak and the occlusion device or (ii) a more accurate numerical model for the leak and the outer ear/earplug system but for a single medium insertion depth of two different earplugs and a combined airborne/structure borne excitation. No study has investigated the contribution to the OE of the miscellaneous couplings of the in-ear device with the earcanal walls (mechanical coupling) and with the occluded acoustic cavity (vibroacoustic coupling) considering all these conditions: (i) different types of in-ear devices (ii) various insertion depths, (iii) bone-conduction stimulation, (iv) presence of possible leakage between the in-ear device and the skin. The quantification of these couplings in these various situations can help clarify how much the in-ear device contributes to the occlusion effect.

This paper focuses on earplugs. The goal of this work is to quantify and discuss the influence of couplings between the earplug, the earcanal walls and the earcanal acoustic cavity on the occlusion effect with the aim of better understanding how the earplug contributes to the occlusion effect. This is carried out using numerical simulations based on a 2D axisymmetric FE model of the outer earcanal/earplug system inspired from Brummund et al.'s work [6]. This model is used to simulate the occlusion effect induced by earplugs as a function of geometrical parameters (earplug length, insertion depth in the earcanal), earplug material, presence of leaks between the earplug and the earcanal walls and assumptions on the couplings between the earplug and the earcanal. Comparisons of simulations between the situation where all couplings are considered (full coupling) and that when the earplug is considered as an infinite acoustic impedance occluding the earcanal (no coupling) are conducted. This allows for determining in which cases the later hypothesis commonly found in LPM models is acceptable. Calculations of powers exchanged between the various domains are also proposed to further quantify the importance of the couplings. Associated results will be shown during the oral presentation.

2. FINITE ELEMENT MODEL OF THE OCCLUSION EFFECT

2.1 Axi-symmetric open and occluded outer ear FEmodel

In this work, the occlusion effect and the powers exchanged at the interface between the earplug/earcanal system are calculated using an equivalent 2D axi-symmetric FE model of the outer ear subjected to a structure borne mechanical boundary load based on Brummund et al's work [6]. Compared to a full 3D anatomically correct outer ear geometry, this axi-symmetric model requires little computational resources which facilitate the implementation of sensitivity analyses with respect, for instance, to geometrical parameters such as earplug insertion depth, earplug mechanical properties or coupling conditions. The proposed model has been shown to compare well with experimental data measured in two healthy human reference groups and two types of earplugs [6].

The proposed FE model is similar to Brummund et al’s [6]. However, there is one main improvement regarding the modeling of the coupling between the outer ear/earplug system and the surrounding medium. Brummund et al assumed that this coupling amounted to a piston-like radiation impedance boundary condition at the earcanal entrance and that free boundary conditions were applied on the tissues in contact with the external air and at the earplug/external air interface for the occluded outer ear. In this paper, the outer ear is assumed to be embedded in an infinite rigid baffle and the vibroacoustic coupling between the outer ear/earplug system and the external air is accounted for using a spherical acoustic domain connected to a Perfectly Matched Layer (PML). This more realistic boundary condition simulates acoustic radiation in a semi-infinite medium (sound waves radiated by the outer ear are not reflected back by the spherical acoustic domain boundary (see Figure 1). This allows one to account exactly for the sound radiation of the outer ear/earplug system (with possible leakage) in the surrounding medium and also for a potential external sound wave (e.g one’s own voice).

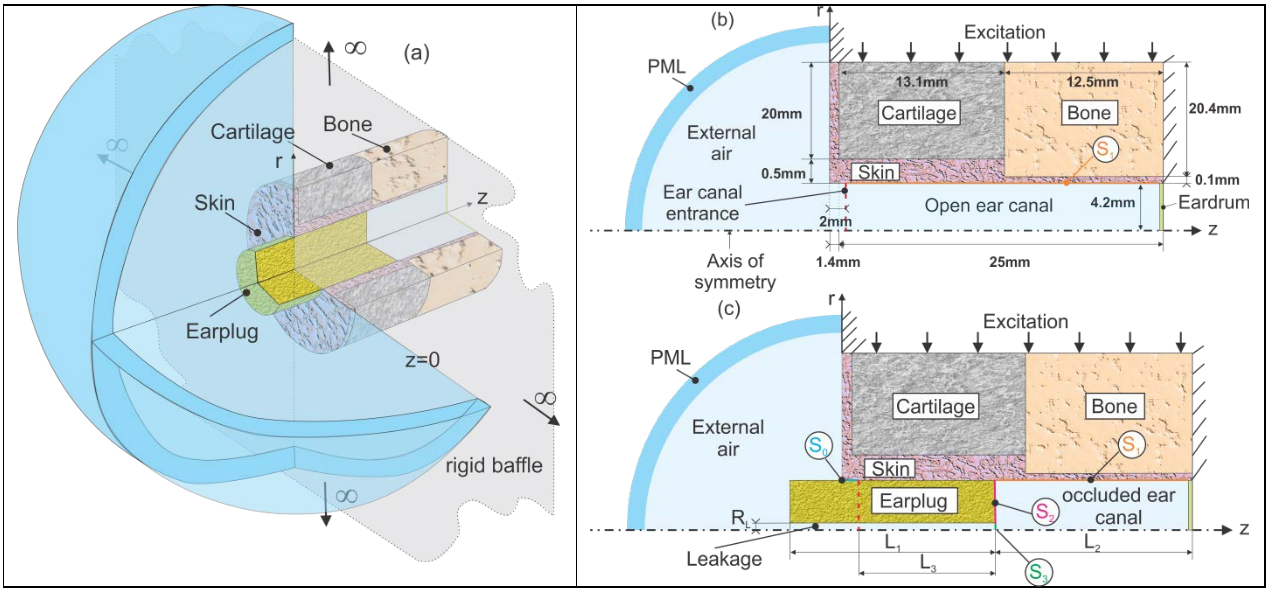


Figure 1 : (a) 3D view of the 2D axisymmetric FE model of the occluded outer ear embedded in a rigid baffle in the plane z=0 adapted from Brummund et al [Brummund 2015].(b) Longitudinal view of 2D axisymmetric FE model of the open outer ear (c) Longitudinal view of 2D axisymmetric FE model of the outer ear occluded by an earplug

The 3D geometry of the occluded ear is shown in Figure 1(a). Since the problem is considered axisymmetric only a cross sectional cut through the (r,z) plane the open outer ear is depicted in Figure 1(b) and that of the outer ear occluded by an earplug with a possible leakage in Fig1(c). The outer ear consists of the earcanal and its surrounding soft (cartilage and skin) and bony tissues. The anatomical landmarks of the pinna are not accounted for in the present model, mainly to preserve the axi-symmetry of the system. The earcanal entrance region geometry is constructed from a protruding outward extension of the cartilage backs the lateral earcanal and the skin tissue on the earcanal walls. The earcanal entrance plane (dotted red line in Fig1(b)) is thus slightly shifted of 2mm inward. Three types of earplugs showed in table 1 are considered in this work: custom type (acrylic), “roll-down foam” and “push-to-fit foam” [10]. These earplugs are assumed to fit the cylindrical earcanal without deforming the earcanal walls upon insertion. The corresponding axi-symmetric geometrical representation of each earplug (cut along the (r,z) plane) is presented in table 1. Note that for the “push-to-fit foam” type, the stem is not considered. In addition, note that the geometry of the “custom” earplug is here simplified to that of the “roll-dow foam” type due to the limitation of the present FE model geometry. Given that the problem is axisymmetric the leakage between the earplug and the earcanal walls is represented by a cylindrical duct going through the earplug with the same symmetry axis. L_1, L_2, L_3 and R_L in Figure 1(c) represent the earplug length, the unobstructed earcanal length, the insertion depth and the leakage radius respectively. The tympanic membrane is assumed to terminate the cylindrical earcanal perpendicularly to its central axis and is modeled as a locally reacting specific acoustical impedance boundary condition [11]. This is a simplification, because it does not allow for the sound radiation that stems from the inertial movement of the ossicles to be considered. The structure-borne mechanical boundary load is introduced normally and uniformly on the horizontal boundaries of the cartilage and bone tissues. It must be noted that this loading condition represents an idealization of the real stress vectors which act on the human tissues, which likely vary in terms of amplitude, phase and direction along the tissue boundaries. In the case of the occluded ear, the earplug is supposed to be coupled mechanically to earcanal walls only from the earcanal entrance plane (dotted red line on Figure 1(c)) to the earplug inserted extremity. When the earplug protrudes from the earcanal, no mechanical coupling between the earplug is supposed to occur (free boundary conditions apply on both the skin and the earplug) on the small interface S_0 (in blue on Figure 1(c)). This interface represents a narrow region of the outer ear just before the earcanal entrance. In the occluded case, the inner face of the earplug is coupled to the earcanal cavity through interface S_2. In presence of leakage, the earcanal cavity is coupled to the leak through interface S_3.

All solid domains are assumed to exhibit linear elastic, isotropic material behavior and the air contained in the unobstructed earcanal part together with the external air are assumed to be a non-dissipative fluid. Due to the small leak diameters, the fluid contained in the leak is modeled as a visco-thermal fluid. The properties of the external ear tissues (Young’s moduli, densities, Poisson’s ratios, and loss factors) and earplugs are derived from [6] and recalled in table 2. Note that in absence of data on the “push-to-fit foam”, the same mechanical properties as the “roll-down foam” have been used as a first approximation. The speed of sound and density of the air are equal to 343.2 m/s and 1.2 kg/m^3 respectively. All solid domains and the earcanal are meshed according to a convergence criterion of 6 elements per wavelength at 2 kHz using quadratic triangular elements.

Table 1: Types of earplugs of interest [10]

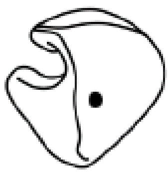
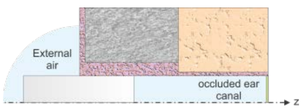
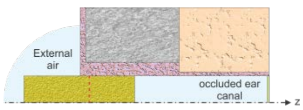
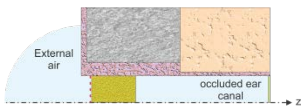
	Custom	Roll-down foam	Push-to-fit foam
			
Corresponding 2D-axisymmetric model of the occluded system			
Material	Acrylic	Foam	Foam
L_1 (mm)	19	19	6

Table 2: Properties of the tissues and earplugs used in the simulation

	Density [kgm^{-3}]	Youn'g modulus [MPa]	Poisson's ratio	Loss factor
Bone	1714	11316	0.3	0.01
Cartilage	1080	7.2	0.26	0.05
Skin	1100	0.5	0.4	0.1
Earplug - acrylic	1050	0.85	0.48	0.1
Earplug - foam	220	0.1	0.1	0.5

2.2 Computation of the simulated occlusion effect, surface average acoustic normal particle velocity and exchanged powers

Both open and occluded models are solved separately using COMSOL Multiphysics 5.4 (© COMSOL Inc). Displacement fields in the tissues, earplug and acoustic pressure field in the earcanal cavity are computed at each node of the mesh.

The OEs are simply obtained through subtraction of the occluded $L_{p,occ}$ and open ear $L_{p,op}$ sound pressure level at the eardrum.

$$OE = L_{p,occ} - L_{p,op} \tag{1}$$

One interesting indicator to quantify the vibratory behavior of the earcanal walls is the surface average normal acoustic particle velocity. It is defined as:

$$\langle \hat{v}_n \rangle = \frac{1}{2S_1}\int_{S_1} \hat{v}_n dS \tag{2}$$

where $\hat{v}_n$ denotes the acoustic particle velocity normal to interface S_1.

In order to better understand the physical mechanisms that explain how the OE is affected by the earplug, its insertion depth in the earcanal and possible leakage, it is useful to consider how the mechanical/acoustical energies flow in the system. Consequently, powers that are exchanged between each domains (tissues, earplug, earcanal cavity) are introduced. Of particular interest are the power exchanged (i) between the earcanal walls and the earcanal cavity (interface S_1) (ii) between the inner earplug surface and the earcanal cavity (interface S_2) (iii) between the leak and the earcanal cavity (interface S_3) (see Figure 1 for notations) . These can be calculated respectively using:

$$\overline{W}_{exc,i} = \frac{1}{2}\Re\left[\int_{S_i} \hat{p}\hat{v}_n^* dS\right] \quad i = 1,3 \tag{3}$$

where $\hat{p}$ is the acoustic pressure in the earcanal cavity, $\hat{v}_n^*$ is the complex conjugate of the acoustic particle velocity normal to the contact surface S_i. $\Re$ denotes the real part of the quantity. Einstein's summation convention is adopted.

3. CONFIGURATIONS OF INTEREST

In order to investigate how the occlusion effect is influenced by the earplug insertion depth, the presence of leakage and the coupling between the earplugs and the outer ear, a full factorial design of experiment 2^k is considered. The two levels of the insertion depth correspond to a shallow ($L_3 = 6$mm) and a deep insertion ($L_3 = 18$mm) for classic foam and push to fit foam earplugs. For the custom earplug one single insertion depth is considered. For the leakage either no leak or a leak of radius 0.5mm is chosen. For the couplings either no coupling or full coupling are studied. No coupling means that the earplug does not affect the vibration of the skin (the skin is free that is no force is applied at the contact interface with the earplug) and the earplug surfaces in contact with the unobstructed part of earcanal and the external air are considered rigid acoustically (no power is exchanged between the earplug and the air in the earcanal, in the leak and in the surrounding environment). In the full coupling condition, the earplug is coupled to the skin (except on the small interface S_0) and to the internal and external air).

4. RESULTS

In this section, preliminary results are presented regarding the influence of the earplug on the occlusion effect. Additional results will be presented regarding the power exchanges in the system during the oral presentation.

Fig2 to Fig4 display OE as a function of frequency for full coupling and no coupling conditions without or with leakage for the custom, “roll-down foam” and “push-to-fit foam” earplug respectively. For the “roll-down foam” and “push-to-fit foam” (Fig3 and Fig4) two insertion depths shallow (left figure) and deep (right figure) are considered.

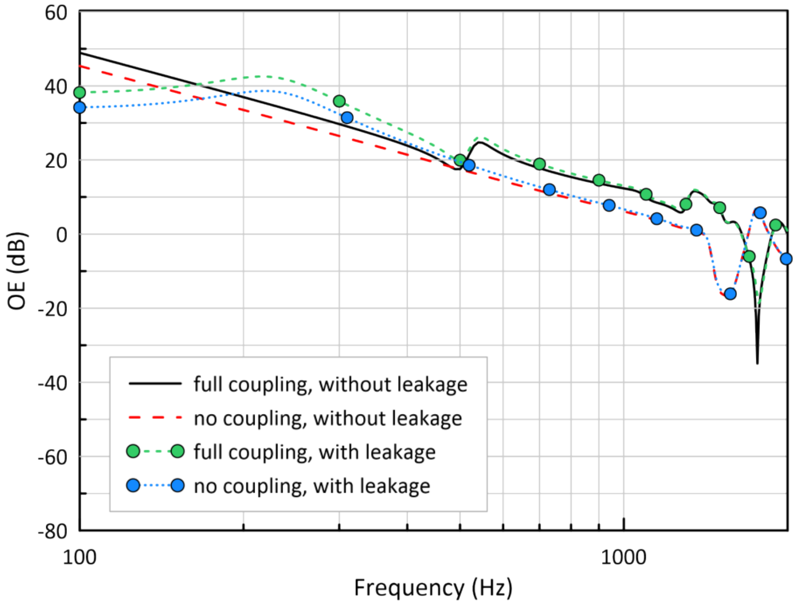


Figure 2 : OE as a function of frequency for full coupling and no coupling conditions for a “Custom” earplug without and with leakage

Consider first the custom earplug (shallow insertion only). Fig2 shows that taking into account the earplug contributes to increase the OE compared to the case where it amounts to an infinite acoustic impedance, whether there is or not a leakage. This increase is more significant above 500Hz. Fig5 shows the surface average velocity of the earcanal walls for full coupling and no coupling conditions for the three earplugs and shallow and deep insertion. Fig5(a) shows that below 500Hz, this velocity is the same in full coupling and no coupling conditions . This would suggest that the contribution of the earcanal walls to the OE would be unchanged and that this would be the sound radiation of the earplug inner face which would be mainly responsible for the slight OE increase. However, it should be noted that a very similar average velocity of the ear canal walls in full coupling and no coupling conditions does not necessarily imply that the acoustic power radiated by the earcanal wall (Eq(3)) is the same both conditions as will be shown in the oral presentation. In fact, in the case of full coupling conditions, complex coupling phenomena between the earplug inner face and the earcanal walls through the earcanal cavity occur and can significantly change the parietal pressure on the earcanal walls without changing significantly the earcanal wall velocity. Above 500Hz, the mean square velocity is slightly reduced when the earplug is accounted for (Fig5(a)). Again the impact of this slight velocity increase on the power injected by the earcanal walls in the earcanal cavity and the resulting respective contribution of the earplug and the earcanal walls will be discussed during the oral presentation. In addition, the effect of the leakage is significant below 500Hz, a decrease of OE at very low frequency and an increase above approximately 150Hz. The frequency of maximum occlusion effect corresponds to the resonance frequency of an Helmholtz resonator whose neck is the leakage and the cavity the unobstructed earcanal cavity [7].

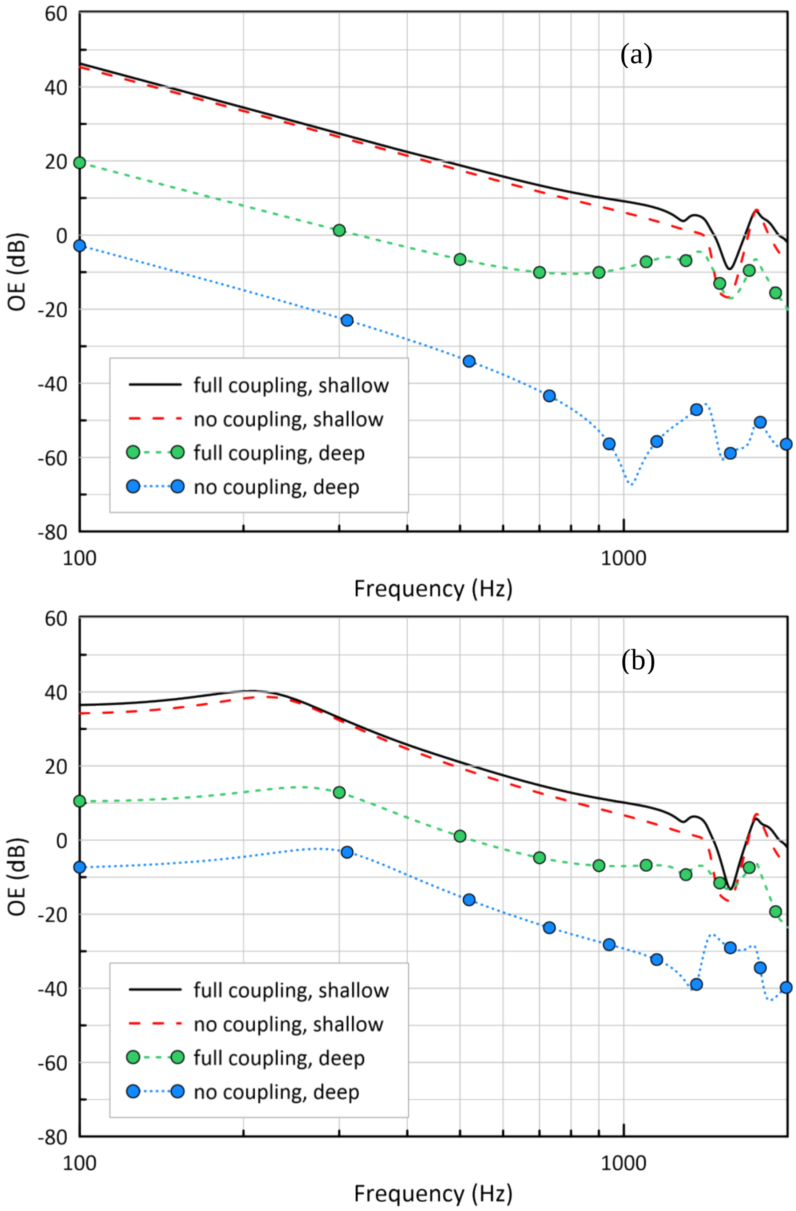


Figure 3 : OE as a function of frequency for full coupling and no coupling conditions for a “Roll-down foam” earplug for two insertion depths (a) without leakage (b) with leakage

Consider now the “roll-down foam” (Fig.3) and “push-to-fit foam” (Fig.4) earplugs. As expected the occlusion effect is much smaller in the deep insertion case compared to the shallow case whether there is a small or no leakage. Consider first the case of absence of leakage (full occlusion) (see Fig3(a) and Fig4(a)). For shallow insertion there is almost no difference between the coupling and non coupling conditions for both types of earplugs. In addition, there is almost no difference between the coupling and non coupling conditions for both types of earplugs on the earcanal wall mean velocity (Fig5(a)). However for deep insertion, there is a large difference when the couplings between the earplug and the earcanal are considered and ignored. For full coupling condition, the OE is much more important than for no coupling condition for both earplugs, indicating the importance of the occlusion device in the contribution to the OE while the earcanal wall velocity is not significantly influenced, except around 1kHz and above for the “roll-down foam” (Fig5(b)). There is also an important difference between the occlusion effect caused by the “roll-down foam” and the “push-to-fit” earplug, the former being much larger than the latter. Consider now the case of presence of a small leakage (see Fig3(b) and Fig4(b)). For shallow insertion the differences are still small between the no coupling and full coupling conditions but larger than in the absence of leakages and they are more important for the “push-to-fit foam” earplug. For a given leakage diameter, the Helmholtz resonator frequency is inversely proportional to the square root of the leakage length which explains why the maximum frequency is higher in the case of the “push-to-fit foam” earplug which is shorter thant the “roll-down foam” earplug. While there was a large difference between the no coupling and full coupling conditions for the OE in the deep insertion case without leakage for both earplugs, the difference is much smaller for the “push-to-fit foam” earplug as seen in Fig4(b).

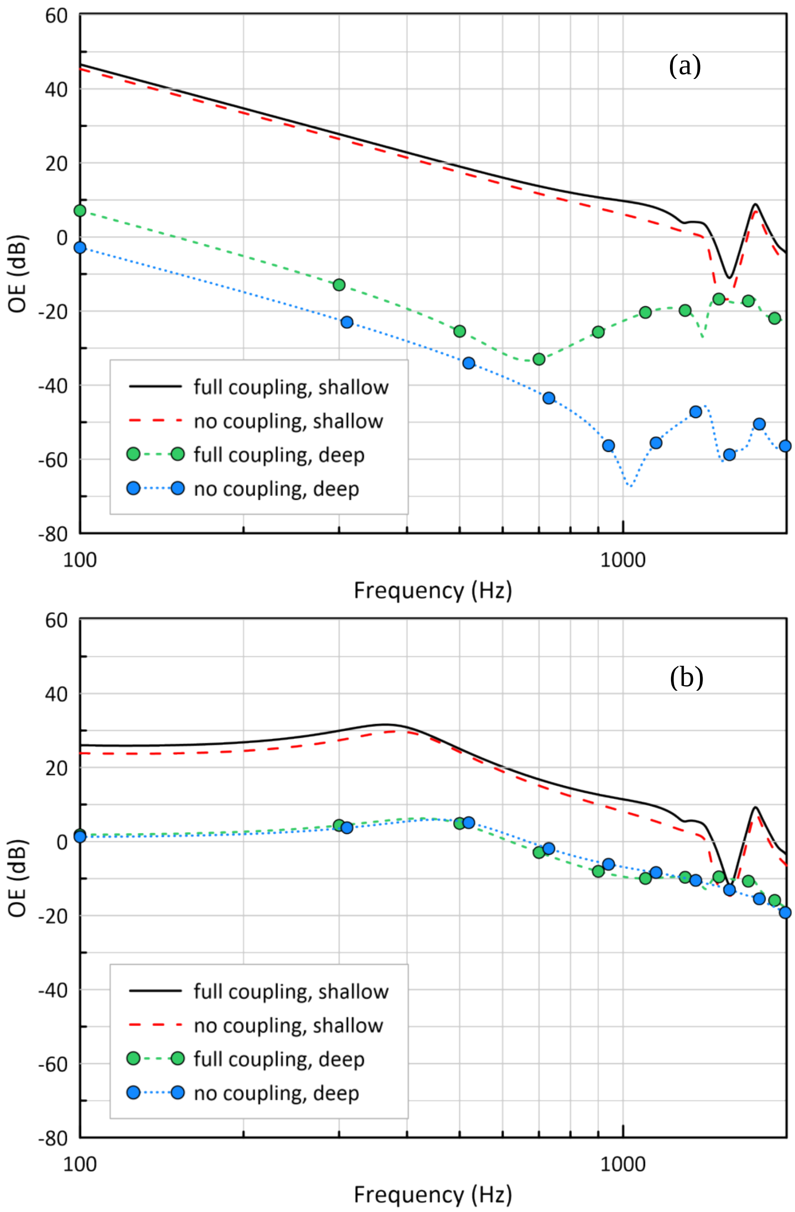


Figure 4 : OE as a function of frequency for full coupling and no coupling conditions for a « push-to-fit foam » earplug for two insertion depths (a) without leakage (b) with leakage.

These figures show that depending on the type of earplugs (materials, importance of the coupling surface between the earplug and the skin) and the insertion depth, the presence of leakage, accounting for all the couplings in the calculation can be necessary. In all the cases previously presented, the earcanal wall mean velocity is not significantly influenced by the presence of the earplug except for the “roll-down foam” earplug above 1kHz. Thus, an investigation based on the powers exchanged at the different interfaces could help clarify how the earplug affects the OE. The corresponding results will be presented during the oral communication.

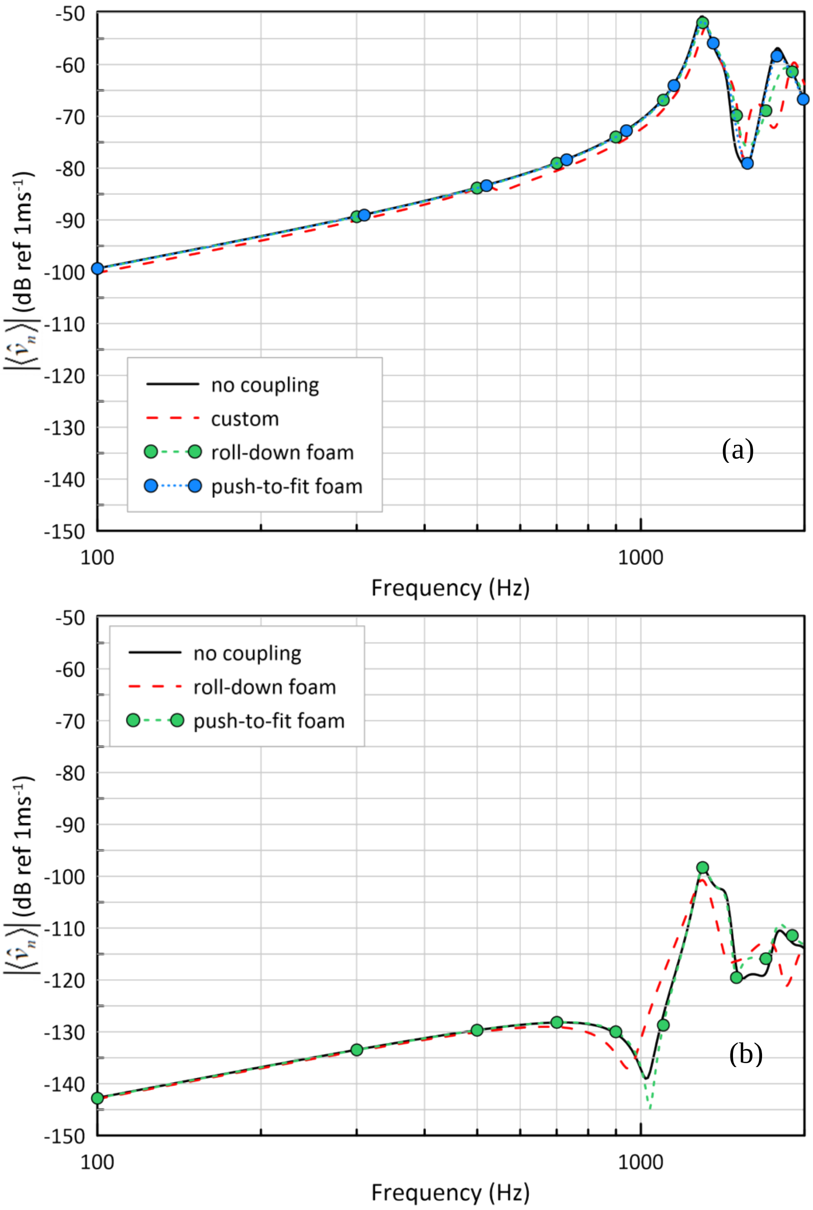


Figure 5 : Modulus of the surface average acoustic particle velocity normal to the earcanal wall (interface S_1) as a function of frequency for full coupling and no coupling conditions for (a) shallow and (b) deep insertion.

4. CONCLUSIONS

In this work, the influence on the OE of the couplings between the earplug, the earcanal walls and the earcanal acoustic cavity have been quantified and discussed in the case of three earplug types (custom, roll-down foam and push-to-fit foam) and two insertion depths (shallow and deep) with the presence or not of leaks between the earplug and the earcanal walls. This study has been carried out using numerical simulations based on a 2D axisymmetric FE model of the outer earcanal/earplug system inspired from Brummund et al.'s work [5].

This work shows that the validity of replacing the earplug by an infinite acoustic impedance, namely not accounting for the earplug/earcanal walls mechanical coupling and the earplug/earcanal cavity vibroacoustic coupling, depends on both the insertion depth and the earplug type (geometry and material properties).

At shallow insertion, for both roll-down foam and push-to-fit foam earplugs, the aforementioned couplings do not significantly influence the OE with and without leakage and an infinite acoustic impedance can be substituted for the earplug. However, in the case of the custom earplug (only shallow insertion), the influence of the couplings on the OE is more significant and that substitution is more questionable.

At deep insertion, couplings between the earplug, the earcanal walls and the earcanal cavitye greatly influence the OE with and without leakage for the roll-down foam earplug. For the push-to-fit foam, the OE is notably sensitive to couplings only in the case without leakage. In all cases, it has also been showed that the earplug does not significantly influence the earcanal wall vibration. Thus, to further understand the sound propagation mechanisms in outer ear/earplug system and investigate how the earplug and the ear canal walls contribute respectively to the OE, calculation of powers exchanged between the various domains is an interesting approach to be explored. Corresponding results will be presented during the oral communication.

Note that the conclusions of this paper should be considered with caution since this FE model includes several limitations. Firstly, its geometry is simplified (e.g. no pinna, possible underestimation of skin thickness in the bony part, custom earplug assumed cylindrical of uniform cross-section, leakage located at the center of the earplug and longer than in reality for roll-down foam and custom earplug). Secondly, there are simplifying assumptions regarding the excitation, boundary conditions and material properties (e.g. tissues, simplified mechanical properties for “push-to-fit foam”). The conclusions obtained with this simplified model should therefore be confronted to those derived using a more anatomically realistic 3D model of the outer ear like Brummund’s [12].

5. ACKNOWLEDGEMENTS

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