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A FINITE–ELEMENT MODEL TO PREDICT INCIDENCE DEPENDENT AND DIFFUSE FIELD NOISE REDUCTION BASED ATTENUATION OF EARMUFFS

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The sound attenuation of Hearing Protector Devices (HPD) can be measured objectively using the “Microphone In the Real Ear” (MIRE) method or with its field counterpart, the F-MIRE method. This method utilizes two microphones (one on each side of the HPD) and provides an indicator called the measured noise reduction NR* defined as the difference between the sound pressure levels outside and underneath the HPD, which is obtained in a single measurement, Correction factors, based usually on diffuse or frontal incidence sound field, can be applied on NR* values to obtain an estimate of the insertion loss (IL) of the HPD, a more common measure of the sound attenuation. Measured attenuation on earmuffs in realistic field conditions have been shown to depend on the direction of the incoming sound, therefore, asking for a revision of the correction factors. Obtaining experimentally these factors that depend on both the external and internal microphone placement together with the incidence angle is cumbersome. Recently, the authors proposed a 3D finite element (FE) model of an Acoustic Test Fixture (ATF) equipped with a commercial earmuff to predict the angle of incidence dependent IL and NR* together with the associated correction factors (Sgard et al, ICA 2016). This FE model was assessed by comparisons with measurements in a semi-anechoic room and proved to reproduce the experimental trends. In this paper, IL and NR* together with the values of correction factors for a commercial earmuff are calculated for a diffuse field excitation and compared with experimental data obtained with an ATF placed in a reverberant room. Diffused field and incidence dependent correction factors are also compared.

Keywords: Hearing protection, finite element methods, earmuff insertion loss

1. Introduction

The sound attenuation of hearing protectors devices (HPD) can be measured subjectively using the “gold standard” attenuation measurement method called the real-ear attenuation at threshold (REAT) [1]. This method is based on the assessment of the differences between the open and occluded ear auditory thresholds measured in a very quiet standardized acoustic environment. Alternatively, the sound attenuation of HPDs can be obtained objectively in laboratory using “Microphone In the Real Ear” (MIRE) [2] method or in the field using “Field-MIRE” method. In the MIRE method, the sound attenuation of HPDs is quantified using the insertion loss (IL) defined as the difference of sound pressure levels (SPL) measured at the eardrum with $\left(L_{p'_t}\right)$ and without $\left(L_{p_t}\right)$ the HPD. This requires two separate measurements. Alternatively, the Field-MIRE method is based on the use of two microphones (one outside and the other between the HPD and the eardrum). It provides an indicator of the sound attenuation obtained in a single measurement and called the measured noise reduction (NR^*). It is defined as the difference between the SPL measured at the external microphone $\left(L_{p'_{ext}}\right)$ in presence of the HPD and at the inner microphone positioned underneath the HPD $\left(L_{p'_c}\right)$. In practice, for an earmuff, the inner microphone is often placed inside the earcup volume close to the ear canal entrance. All these methods have their pros and cons and lead to different attenuation results [3]. However, these attenuation data can be compared by introducing correction factors derived from ensemble averages which relate the REAT, IL and NR^* attenuation values [4]. The relations linking these psychoacoustical and physical attenuation values are given by $REAT = IL + PN$ and $IL = NR^* + TF'_{canal} - TF'_{ext} + TFOE$. In the previous equations, $IL = L_{p_t} - L_{p'_t}$, PN denotes the physiological noise, $NR^* = L_{p'_{ext}} - L_{p'_c}$, $TF'_{canal} = L_{p'_c} - L_{p'_t}$ is the transfer function between the sound pressure at the inner microphone and the sound pressure measured at the eardrum for the occluded ear, L_{p_o} is the SPL measured at a microphone located at the centre of the head in the absence of the subject, $TF'_{ext} = L_{p'_{ext}} - L_{p_o}$ is the transfer function between the sound pressure measured at the external microphone in presence of the HPD and the one measured at a microphone located at the centre of the head in the absence of the subject, $TFOE = L_{p_t} - L_{p_0}$ is the transfer function of the open ear. Note that all quantities are expressed in decibels. The term $NR^* + TF'_{canal} - TF'_{ext}$ in Eq(2) is referred to as NR and is defined as the difference between the SPL at the centre of the head in the absence of the subject and at a microphone at the eardrum location for the occluded ear. Eq(2) indicates that if NR^* is known, IL (and therefore $REAT$) can be retrieved by summing up correction terms which need to be determined in some way. In the literature, these global correction factors are generally approximations derived from ensemble averages and few details are given on how these factors are affected by various parameters such as the positioning of the microphones, the physical characteristics of the individuals, the sound field, etc. as discussed by Nelisse et al [4]. In addition the importance of the relative contribution of the abovementioned factors ($TF'_{ext}, TF'_{canal}, TFOE$) is rarely tackled. The F-MIRE method has been used successfully for continuous measurements on earmuffs in real field environments where the sound field can depart significantly from a diffuse field and may show strong directionalities [5]. These field attenuation measurements have been shown to depend on the direction of the incoming sound, therefore, asking for a revision of the correction factors [3,6]. Obtaining experimentally these factors that depend on both the external and internal microphone placement together with the incidence angle proves to be cumbersome. Gaudreau et al [7] proposed a finite-element (FE) model of an earmuff coupled with an artificial head called ATF (artificial test fixture) exposed to a directional sound field to investigate the angle dependence of NR^*. The model proved to capture adequately the experimental data obtained in a semi-anechoic room for several incidence angles. While several studies have been made on the influence of the sound incidence on the *TFOE* [8–13], no study has dealt with the other correction factors TF'_{ext}, TF'_{canal} or with the overall correction factor $TF'_{canal} - TF'_{ext} + TFOE$. Sgard et al [14] pursued this work by investigating the overall correction factor relating IL and NR^* together with the individual contribution of the various terms appearing in this correction factor using both a 3D finite element model of an ATF with and without an earmuff (EAR1000 model® 3M Hearing Protection, U.S.A.). Overall the proposed FE model gave the trends for the IL and the global correction factor $IL - NR^*$ even though discrepancies at mid and high frequencies were observed. Besides confirming that the sound attenuation performance of earmuff depends on the incidence angle, Sgard et al demonstrated that if an NR-based measurement method is used to evaluate sound attenuation on the field, it is important to use incidence angle and frequency dependent correction factors when relating NR^* to IL. This paper is an extension of Sgard et al's work [14] to a diffuse field excitation.

The objective is to use the previous 3D finite element model to calculate the values of IL, NR^* together with the correction factor relating IL and NR^* when the ATF equipped with an earmuff is excited by a diffuse field. Besides providing a tool to understand finely the acoustical behavior of the system, another advantage of the FE model is that each individual correction factor can be calculated readily individually to determine their relative importance. $TFOE$ is obtained from the ATF model without earmuff and the global correction factor $TF'_{canal} - TF'_{ext} + TFOE$ can be directly calculated from the difference between IL and NR^*. To assess the validity of the model, the simulated diffuse field attenuation results and correction factors are compared with experimental measurements obtained on an ATF equipped with an earmuff placed in a reverberant room. Comparisons between diffuse field and angle of incidence dependent correction factors obtained in [14] are then discussed.

The paper is organized as follows. First, the FE model and the methodology are recalled. Second, the experimental set-up is described. Third, the model is assessed based on comparisons with experimental data. Finally, an example of comparison between diffuse field and angle of incidence dependent global correction factors is presented.

2. Modeling of the system

The modeled configurations are depicted in Figure 1. They consist of an ATF coupled (Figure 1(a)) or not (Figure 1(b)) with an earmuff through a silicone pad which simulates the external flesh in contact with the earmuff. The ATF and earmuff CAD correspond to a G.R.A.S CB-45® (GRAS Sound & Vibration, Denmark) and an EAR1000 model, respectively. The earmuff is made up of five components (i) the plastic earcup, (ii) the comfort cushion, (iii) a rubber plug that links the plastic earcup to the headband, (iv) the headband and (v) the sound absorbing foam pad. In this study, only the first four components are considered, the foam pad being ignored to simplify the model. The ear canal (EC) in the ATF is circular cross section cylinder with an inner lining made of silicone that mimics the skin part in contact with the interior of the EC. The EC is terminated by a tympanic membrane which acts as a locally reacting boundary impedance condition (eardrum part of the IEC711 coupler impedance [15]). Fixed boundary conditions are applied on (i) the outer boundaries of the silicone ring and (ii) the circumferential part of the silicone pad together with its inner face in contact with the ATF. The system is excited acoustically by a diffuse field modelled as a superposition of 134 incoming uncorrelated plane waves (see Figure 1(f)). For the sake of simplicity and computational costs, only the sound transmission through the right earmuff is considered while the left one is considered as rigid acoustically. Note that to avoid the appearance of a parasitic compression resonance in the results, the comfort cushion is not excited on its flanks in contact with the external air [7].

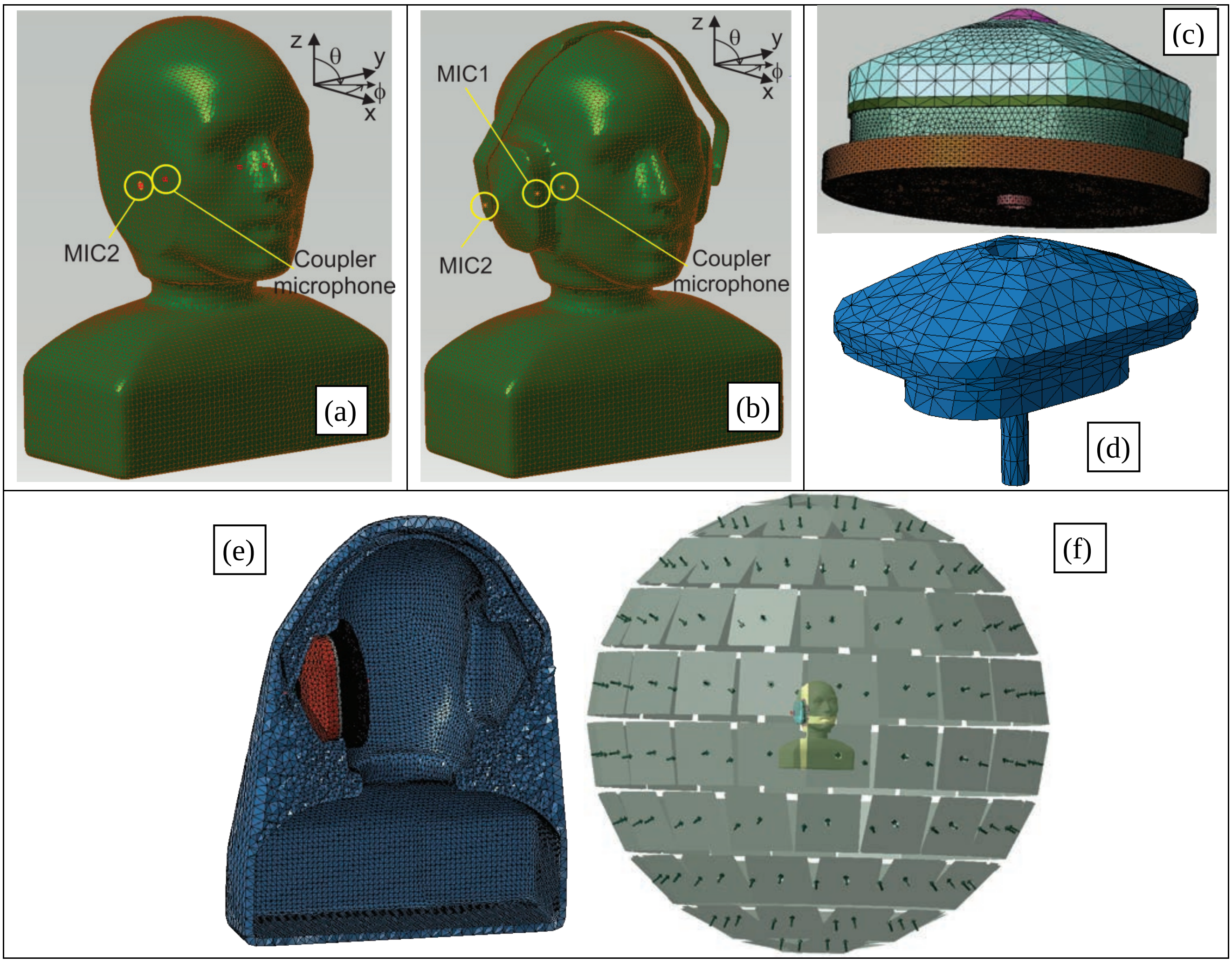

Figure 1: Skin mesh of (a) ATF with earmuff (b) ATF without earmuff (c) Mesh of plastic shell, comfort cushion, rubber plug, artificial skin pad and skin ring (d) Mesh of internal cavity and ear canal (e) Mesh of convex external volume around the ATF (f) diffuse field as a superposition of uncorrelated plane waves

The solid domains (earcup, silicone disk, silicone ring) are modeled as elastic isotropic solids The cushion is modeled as an equivalent viscoelastic material with a frequency dependent complex Young's modulus whose values depend on the compression rate of the cushion [16]. The effect of the headband force is accounted for in the model by using an averaged compressed cushion static thickness corresponding to a compression rate of 20.5% and the corresponding cushion mechanical properties [17]. The sound propagation in the external and internal acoustic domain is governed by Helmholtz equation. Since the external fluid is infinite, a Perfectly Matched Layer condition [18] is applied on the outer boundary of a convex finite acoustic volume surrounding the head/torso/earmuff system to absorb the acoustic waves scattered by the system. The coupled problem is solved using the FE method. All domains are meshed using 10-noded quadratic tetrahedrals. The mesh is chosen in order to capture well the spatial variations of the geometry. The solver relies on a high-order adaptive FE technology that adapts automatically the order of interpolation on each element based on the mesh size and the frequency. At lower frequencies, low-order interpolation is used and the computations are much faster, whereas at higher frequencies, high order interpolation is used and more effort is required. This approach allows for a very good accuracy of the solution for a given mesh even at high frequency and a higher convergence speed. The details of the FE model are provided in [7]. All the calculations have been carried out with the commercial software Virtual.Lab 13.7® (LMS/SIEMENS, Germany). The properties used for the different domains are summarized in Table 1. The model is used to calculate the SPL at the eardrum, at the ear canal entrance for both unoccluded and occluded conditions. In the case of the ATF with earmuff, the SPL at the centre of the headband (see Figure 2b) is also evaluated in order to calculate NR^{*} and TF'_{ext}.

Table 1: Physical properties of the various domains

	ρ (kgm^{-3})	E (Pa)	ν	Loss factor η	c (ms^{-1})	Radius (mm)	Thickness/Length (mm)
Earcup+backplate	1200	2.16e9	0.38	0.05	-		
Cushion	142.8	E(f) see [17]	0.4	η (f) see [17]	-		10.9
Plug	806	1e8	0.48	0.5	-		
Silicone pad (flesh)	900	340e3	0.43	0.15	-	57.5	10
Silicone ring (skin)	1150	420e3	0.43	0.2	-	5.45	13
Ear canal + internal cavity (air)	1.213	-	-	0.001	342.2	3.75	27
External air	1.213				342.2		

3. Experimental set-up

In order to evaluate the model, a G.R.A.S CB-45® ATF equipped or not with an EAR1000 was placed in a reverberant room of volume 211 m^3 (see Figure 2a). The diffuse field was generated using four loudspeakers (MACKIE HD 1531) with an approximate overall SPL of 120 dB. As in the model, the sound absorbing foam was removed from the earcup and the usual silicone pinna of the ATF was taken out and replaced with a homemade transparent silicone pad. A microphone (MIC1) was placed inside the earmuff, measuring the internal acoustic pressure close to the ear canal entrance and a second microphone (MIC2), measuring the external acoustic pressure was positioned outside the attachment of the headband (see Figure 2b).

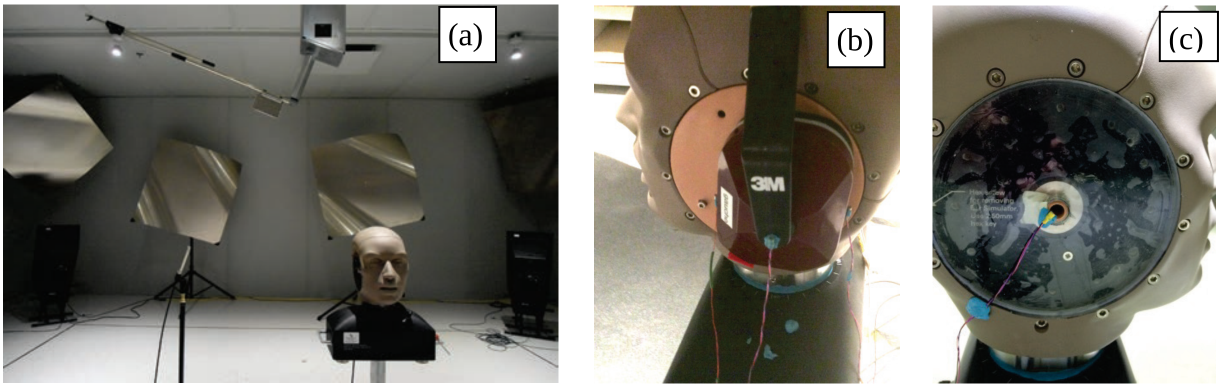

Figure 2: Experimental set-up (a) ATF (no earmuff) in a reverberant room (b) external microphone MIC2 (earmuff with OEM silicone pad) (c) internal microphone MIC1 and homemade silicone pad on right side

4. Evaluation of the FE model

In order to estimate the various correction factors the model should first be able to predict adequately the sound pressure levels at the positions mentioned in section 1. The proposed FE model has already been assessed regarding the angle of incidence dependent NR^{*} [7] together with IL and global correction factor $IL - NR^{*}$ [14]. Figure 3(a) (respectively (b)) shows the comparisons between predicted and measured 1/3rd octave band IL (respectively NR^{*}) for the protected right ear in diffuse field conditions. Figure 3 indicates that the model allows for capturing fairly well the frequency dependence of IL and NR^{*}. However, above 2000Hz, there are amplitude discrepancies between the model and experimental data. In the high frequency range, IL is mostly affected by the modes governed by the internal earmuff acoustic cavity but also by a coupling between the cushion and the internal cavity [17]. Ongoing work on earmuff modelling shows also that the cushion model has a strong influence on the acoustic response of the earmuff in mid and high frequencies and thus should be as realistic as possible. Differences between the prediction and measurement could thus be attributed to errors in the model such as (i) inadequate cushion model to capture the possible sound transmission phenomena through the cushion and coupling phenomena with the internal cavity that may occur at mid and high frequencies (ii) inadequate physical parameters for the silicone disks and rings and damping in the system. They could also be attributed to experimental conditions such as (i) compressed cushion thickness accurate evaluation due to spatial compression inhomogeneities (ii) aging of the cushion since it has been first characterized mechanically.

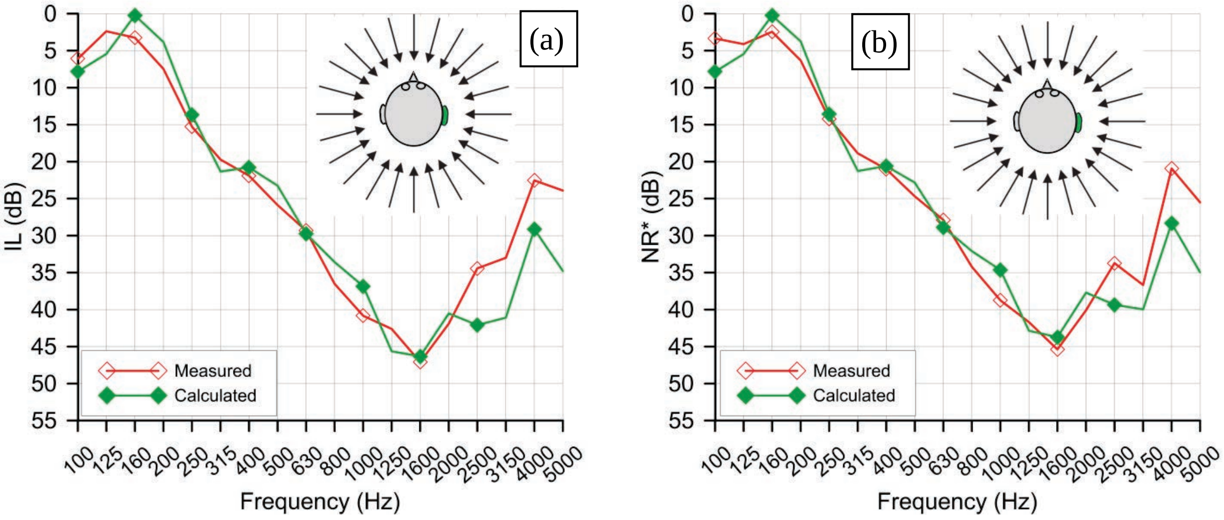

Figure 3: Predicted and measured IL (a) and NR^* (b) for the right ear earmuff

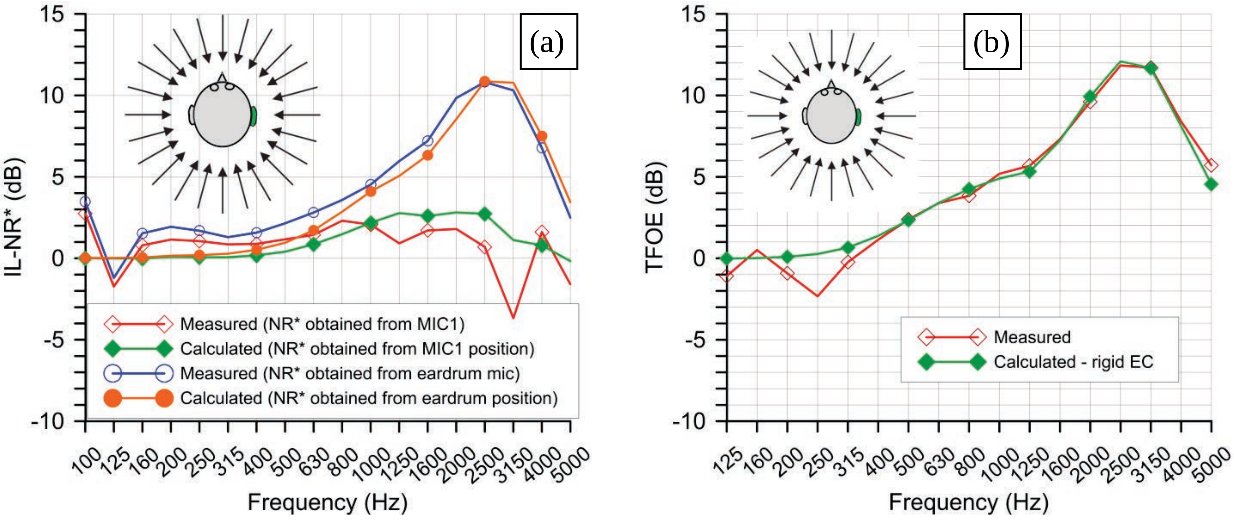

Figure 4: Predicted and measured global correction factors ($IL - NR^*$) of the right ear earmuff (a) - Predicted and measured $TFOE$ (b)

Figure 4(a) displays the comparisons between predicted and measured 1/3rd octave band global correction factor $IL - NR^*$ when the inner microphone is located at the ear canal entrance (MIC1) or at the eardrum. In both cases, there is an overall good agreement between measurements and calculations. It is seen that the global correction factor is small (less than 3dB) over the whole frequency range when MIC1 is used whereas when the inner microphone is positioned at the eardrum, the global correction factor is small at low frequency but can reach significant values at medium and high frequencies (maximum of 12dB at the occluded ear canal resonance). In both cases, TF'_{ext} is small (not shown here). When MIC1 is used TF'_{canal} and $TFOE$ compensate each other while when the inner microphone is at the eardrum the overall correction factor is mainly due to *TFOE* . Figure 4(b) shows the comparison between the measured and predicted diffuse field *TFOE* . Again the agreement is excellent.

5. Results

Figure 5(b) plots global correction factor $IL - NR^*$ when the inner microphone is located at ear canal entrance (MIC1) in the case of an excitation by a monopole that can be located at various positions around the ATF [14] and a diffuse field. Figure 5(a) displays the four positions of interest of the monopole symbolized by a loudspeaker. Two elevation angles θ=90° and 45° and two azimuthal angles ϕ=90° (pointing at the left ear) and ϕ=270° (pointing directly at the right ear) are considered. The angle of incidence global correction factor is small at low frequency but can reach values of up to 10dB (negative or positive) at medium and high frequencies depending on the incidence angle. It does not vary monotonously. The largest amplitudes are obtained for the protected ear directly exposed to the source (θ=90°, ϕ=270°). On the contrary, the diffuse field global correction factor is negligible at low and high frequencies and is less than 3dB over the whole frequency range.

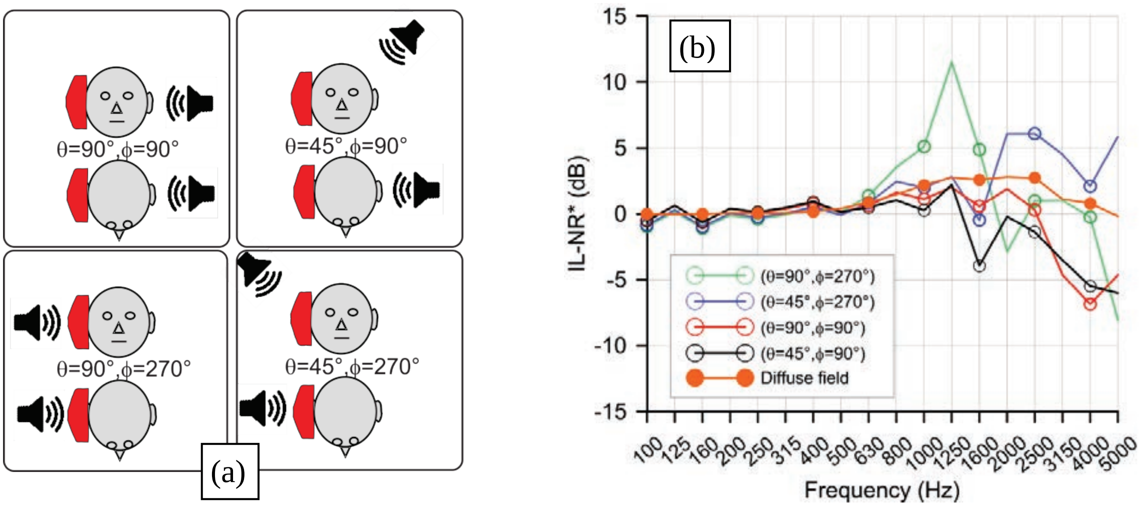

Figure 5: Comparison between diffuse field and angle of incidence dependent global correction factors

6. Conclusions

In this paper, a 3D FE model of an ATF with and without an earmuff, excited acoustically by a diffuse field has been developed to calculate the earmuff IL and NR^* together with various correction factors relating these two indicators. The model has been evaluated by comparisons with experimental data obtained in a reverberant room. Overall the proposed FE model gives the trends for the IL and NR^* even though amplitude discrepancies can be observed at mid and high frequencies. The sources of these discrepancies are currently under investigation in order to improve the correlation between the FE model and the experimental results. The predicted and experimental diffuse field global correction factors $IL - NR^*$ and *TFOE* are in good agreement. It has been found that the global correction factor can reach important values if the inner microphone is located close to the eardrum. Its values are close to those of the *TFOE* . When the inner microphone is placed at the ear canal entrance, the diffuse field global correction factor is much less important with values less than 3dB over the whole frequency range. It has also been shown that the values of diffuse field correction factors based on a microphone located at the ear canal entrance are much less important than those obtained in a directional sound field. If an NR-based measurement technique is used to evaluate sound attenuation on the field, previous work shown that it is important to use incidence angle and frequency dependent correction factors to relate NR^* and IL . In this work, it is shown that in diffuse field conditions NR^* is close to IL and thus correction factors are small.

Acknowledgments

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