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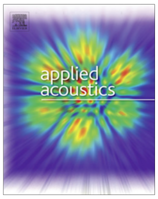

Investigation of the variability in earplugs sound attenuation measurements using a finite element model

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ABSTRACT

Several studies report that an important range of attenuation can be observed in the measurement of earplugs (EP) sound attenuation. This important range of attenuation can be attributed to several intricate factors; the most commonly cited being the earplug insertion depth, the presence of leakages, the inter-subject ear canal (EC) geometrical variations, and the dynamical properties of the human EC tissues. The purpose of this work is to investigate the effect of these individual factors on the insertion loss (IL). Firstly, a finite element model of the EC surrounded by human external tissues and occluded by two types of EPs (foam and custom molded) is developed to predict the IL. Secondly, comparisons between attenuation measurement on human subjects and IL predicted by the model are carried out to validate the model. Thirdly, the effect of the aforementioned factors is quantified using the proposed model in order to explain the variability observed in the attenuation measurement on human subjects. It is found that the presence of leakages and the EP insertion depth are mainly responsible for the variability of the predicted EPs IL at frequencies <at 1 kHz whereas at higher frequencies it is the EC inter-individual geometrical variability.

1. Introduction

According to the World Health Organization, about 120 million workers worldwide are regularly exposed to noise levels that can permanently damage the auditory system. A widespread solution used to protect the workers from noise overexposure consists in using hearing protection devices (HPDs) such as earplugs (EPs) or earmuffs. In practice, it is important to measure the HPDs attenuation to know the degree of protection that can be achieved for the workers and also to choose adequately HPD. This attenuation can be measured by numerous methods (see [3] for a comprehensive review), such as the standardized real attenuation at threshold method (REAT) [1], the microphone in real ear method (MIRE) [2], or its “in situ” variant, the field microphone in real ear method (F-Mire) [6,33]. Several studies report that these methods, even when they are performed in laboratory conditions, can lead to important variations in the attenuation measurement of a given type of HPD. This work investigates this issue using a numerical model, in the case of a custom molded EP (CMEP) and a foam EP (type Classic, 3M).

Berger [5] reports that a REAT range of attenuation as much as 26 dB can be achieved for a given foam EP (type Classic, 3M) based on a compilation of 188 tests conducted in 29 different facilities. A similar range of attenuation about 25 dB has been found by Brueck [7] for insertion loss (IL) measured on 12 subjects wearing various EPs, including the Classic EP. Murphy et al. [17] have reported range of attenuations even larger, about 35 dB for the Classic EP and about 40 dB for the CMEP (24 adult subjects tested in 6 different laboratories). In a recent study [18,19], investigated the relationships between REAT, IL, and noise reduction (NR) measured on 29 subjects wearing various hearing protectors. For each of the three attenuation indicators examined, an important range of variation about 25 dB was obtained for the Classic EP and for the CMEP. This variability in the measured attenuation can be due to several factors detailed in the following.

The EPs insertion depth is known to affect their attenuation at low frequency ([5] for the Classic EP; [26,27] for the CMEP). In the case of the IL measurement, the presence of leakages due to the introduction of a miniature microphone inside the occluded EC can dramatically reduce the attenuation [24,4]. The inter-subject and intra-subject (from the left ear to the right ear)

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geometrical variations of the EC have been frequently mentioned as a factor that can affect the sound pressure level (SPL) in both the open EC [25] and the occluded EC [11,31]. The inter-individual variability of the dynamic properties of the EC tissues can also result in SPL variations in the EC [12,8]. Even if these factors are frequently reported in the literature to qualitatively explain the variation of the EP attenuation measurements, their precise impacts on the attenuation have never been investigated and quantified separately. The research presented in this paper aims at carrying out this investigation task through the development of a finite element model to predict the IL of EPs. Past works dealing with hearing protection modeling are reviewed hereafter.

A 2D axisymmetric model is preferable due to the reduction of the number of degrees of freedom of the final system to be solved and hence the associated resolution time, especially in the case of sensitivity analyses which require a large number of simulations [31]. In addition, a 2D axisymmetric configuration for the EC is often used in attenuation measurement set-ups such as acoustical test fixtures and in house experimental set-ups dedicated to validate numerical models that can be found in literature (see [30,31,11,12,14,10]). The validity of a 2D axisymmetric description of the ear canal in the open case [25] and in the occluded case [28,31] were demonstrated, but these studies were restricted to rigid walled ear canals and to fixed boundary conditions around the EP walls, (i.e. there was no sound path through the tissues surrounding the ear canal). Different geometry reconstruction methods were compared in order to use a 2D axisymmetric FE model of the EC–EP system rather than a full 3D model to predict an individual IL. The authors confirmed that a rigid walled occluded EC model tended to overestimate the attenuation which can be measured in "real life" situations or on ATF because the skin tissues around the EC were not accounted for.

The external human EC includes different tissue domains along its walls and is thereby a complex system to model. In Viallet et al. [29], the authors accounted for the biological tissues surrounding the ear canal via a mechanical boundary impedance condition but did not take into account the part of the incident acoustic energy which could flow directly through the skin into the unoccluded part of the EC. The geometrical reconstruction of an individual EC including the surrounding tissues is a difficult and highly time consuming process (see [8,22]). In recent works [32], a 2D axisymmetric model of the silicone-lined EC to mimic the effect of the skin was developed to study the effect of the artificial skin present in the available ATF. This model was validated using attenuation measurement on the ATF 45CB (©G.R.A.S. Sound & Vibration AS, Denmark) without the pinna. The results showed the potential of such a model to predict the sound attenuation of EPs. However further development was required to include the other human tissues, namely the soft tissues and the temporal bone. In Viallet et al. [30], the 3D FE model developed by Brummund et al. [8] for the auditory occlusion effect was adapted to the case of an airborne excitation. This model includes the human tissues mentioned above. The geometrical characteristics of this 3D FE model were used to reconstruct an equivalent 2D axisymmetric geometry using equivalent volumes for the surrounding tissues and equivalent length and volume for the EP. This 2D axisymmetric model provided encouraging results for the comparison between simulated IL and measurements on human subjects. However it was limited to one specific individual configuration which does not correspond to an average EC and therefore cannot be exploited to test inter-subject geometric EC variability.

As mentioned above, the main objective of this work is to investigate the effect of several factors responsible for the variability of the EP attenuation measured on human subjects namely the EP insertion depths, the presence of leakages, the inter-individual EC geometrical variations, and the material mechanical parameters of both the EC tissues and the EP. This objective is achieved via a three-step methodology detailed hereafter.

First, a 2D axisymmetric FE model of an equivalent EC representative of an EC ensemble averaged and occluded by two types of EPs (Classic and CMEP) is developed to simulate their ILs. In the following, the term «average model» refers to an equivalent model representative of an EC ensemble averaged. This model is based on the geometrical data used in Viallet et al. [31] for the inner part of the EC and in Brummund et al. [8] (also adapted in [30]) for the tissues surrounding the EC (see Section 2.1). In the rest of the document, the term «inner part» refers to the EC air cavity which can also be coupled to the EP in the occluded case.

Second, the model is validated using comparison between simulated ILs and attenuation measurements on human subjects available in the literature ([26,27,5]; see Section 2.2) and carried out by the authors ([18,19]; see Section 3). The use of direct comparisons with measurements on human subjects rather than a dedicated experimental set-up is supported by the fact that the construction of such a set-up with materials replicating the human tissues and with a variable cross section inner EC geometry is a very hard and time consuming task which could not be accomplished in the framework of this research. In addition, the effects of the factors that the authors want to investigate (for example the inter-individual EC geometrical variations) naturally occur in measurements on human subject while a validation set-up would correspond to a unique configuration.

Third, the model is used to explain the effect of the different aforementioned factors responsible for the variability observed in attenuation measurements. The methodology related to the introduction of these factors is detailed in Sections 2.2 (EPs insertion depth), 2.3 (presence of leakages), 2.4 (inter-subject EC geometrical variation), and 2.5 (material properties). Regarding the EPs insertion depths, the EPs inserted length used in the average FE model are chosen to match typical insertion depth values available in the literature ([5], for the Classic EP; [26,27], for the CMEP). The presence of leaks is introduced in the model via a thermally conducting and viscous air cavity through the EP. For the EC geometrical variations, the inner part of the EP–EC system geometry is modified using data (14 realistic EC geometries) proposed by Stinson and Lawton [25] and used by Viallet et al. [31]. For the effect of the material properties, sensitivity analyses are performed using the average FE model in order to quantify the impact of the dynamical properties of the EC surrounding tissues and the EPs material.

2. Modeling strategies

2.1. Average 2D axisymmetric finite element model of the open and the occluded ear canal

2.1.1. Average geometry of the open and the occluded EC

The geometries used for both the open and the occluded EC are described in Figs. 1–3, respectively.

The geometric inner part of the EC is based on the geometrical data of the ECs measured by Stinson and Lawton [25] for a rigid walled open EC. A collection of 14 ECs with realistic 3D geometries was used to create 2D axisymmetric geometries with variable cross sections along the z-axis according to the approach described in Viallet et al. [31]. An average 2D axisymmetric geometry for the inner part of the EC was created using the average cross-section area function for the human EC documented in Stinson and Lawton [25, see Fig. 12]. It should be recalled that in Stinson's work, the fourteen individual area functions have been scaled to a common length of 30 mm and the mean calculated to define the average cross section area function. A 3D geometric model of the EC with