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Objective assessment of the sound paths through earmuff components

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A B S T R A C T

This paper proposes an objective measurement methodology to assess the sound transmission paths through various earmuff components (cup, cushion, back-plate, foam insert, silicone flesh) and estimate the vibroacoustic couplings between them. The measurement methodology is applied to two different commercial earmuffs. For each Hearing Protection Device (HPD), the different sound paths are assessed, by analyzing separately the vibroacoustic behavior of each HPD component. In particular, the Insertion Loss (IL) of the lateral walls of the cushion is assessed, with and without pumping motion. The effect of the coupling between the different parts is also investigated from the comparison of the separate components with the complete earmuff. As shown in past studies, results confirm that the acoustical behavior of an earmuff is governed by the pumping motion and air leaks at low frequency and by the sound path through the cup and the cavity resonances at high frequency. However, at mid frequency, new counter-intuitive results are revealed. It is found that earmuffs do not behave as their weakest element, but rather as the one which has the highest attenuation. It is also observed that the foam insert can also decrease the IL. Complementary tests using other absorbing materials show that this effect could mainly be attributed to the absorption behaviors of each material at medium frequencies.

1. Introduction

When occupational noise cannot be reduced at the source or along its propagation path, individual Hearing Protection Device (HPD) remains the short term most used solution to protect workers against noise exposure because of its small cost and its simplicity of implementation. The work presented in this paper deals with passive earmuffs. As shown in Fig. 1(a), an earmuff is an assembly of an ear cup (single cup or dual cup) filled with a foam lining and of a cushion which ensures the seal between the ear cup and the flesh.

The use of such passive earmuffs is however associated with three important issues. The first one is the discomfort problem caused for example by the static pressure induced by the earmuff headband force which may reduce the wearing time recommended to limit noise exposure [1]. The second one is associated with the assessment of the real protection brought by the HPD. The REAT (Real-Ear Attenuation at Threshold) test [2] also called "gold standard" which is used to quantify the Noise Reduction Rating (NRR) generally overestimates the performance of the HPDs [3]. Measurement techniques in workplaces such as the F-MIRE (field microphone-in-real-ear) method may be in the future better tools to rate the individual field attenuation. If such techniques exist for earplugs, they need to be adapted and improved for earmuffs by determining the optimal location of the acoustic sensors and the individual compensation factors. The third issue is associated to the optimization of the earmuff attenuation efficiency for the individual (e.g., dimension of the cup, physical and acoustic comfort criteria...). This sound attenuation efficiency can be quantified using an indicator called the Insertion Loss (IL) defined as the difference between the sound pressure at the eardrum without and with the earmuff.

Developing a numerical modeling tool of the vibroacoustic behavior of an earmuff was proposed to help solving these issues [4]. As explained in [4], past studies proposed several modeling approaches to predict the sound attenuation of earmuffs ranging from simple lumped models to sophisticated Finite Element Models. However, the validity of the assumptions made in the literature to model the acoustic behavior of each component, in particular the cushion is hardly discussed. An experimental analysis of the sound transmission paths is therefore proposed in this paper to better understand the acoustic behavior of the earmuff to be

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modeled in order to target ultimately the right level of modeling of each component.

The present paper carries out a detailed analysis of the sound pathways through earmuff components, including their coupling effects. Firstly, the sound pathways through earmuff components (cushion, cup) with and without vibroacoustic couplings between the various components are assessed experimentally. Then the specific effect of the foam lining on the sound attenuation is analyzed. This paper is limited to the study of the main HPDs components (cushion, cup and foam insert) and their effect on the sound attenuation. The effect of the flesh on the acoustic behavior of the HPD is not investigated in this work. To achieve these goals, an objective measurement method is proposed to provide robust experimental data of the earmuff components attenuations, using the IL as acoustical indicator. This method is applied on two commercial earmuffs with different designs. An original experimental setup is proposed, based on the concept of a baffle instrumented with microphones. Because an earmuff is a highly insulating system, the design of the experimental setup required very special care (i.e., mounting conditions, sealing...).

The paper is organized as follows. Next section presents a literature review regarding the previous works dealing with the analysis of the sound paths through an earmuff. Section 3 describes the experimental setup and the measurement methodology. Finally, the results are shown and discussed in Section 4.

2. Literature review on the analysis of the sound paths through an earmuff

2.1. Conventional sound transfer paths

When considering hearing protection using earmuffs, a classic sound path description from the literature as given by Berger [5], and Gerges and Casali [6] sets the limitations of the HPD performance. These four paths are presented in figure (d). Path (1) corresponds to the acoustic leakages at the contact between the cushion and the flesh which sometimes may be caused by the design of the HPD [7]. The main effect is the decrease of the attenuation efficiency below 1 kHz. Path (2) corresponds to The pumping motion of the cup, also called “protector vibration” [8,9] or “HPD inertia effect” [10]. It is due to the softness of the cushion and the human flesh which act together with the earmuff cavity as a spring-damper system: the cup plays the role of a mass, and vibrates as a rigid body over the cushion. Path (3) corresponds to the direct sound transmission through the earmuff. Path (4) corresponds to the Bone Conduction (BC), which includes any sound path to the cochlea other than air conduction.

Several past studies analyzed the different sound paths enumerated above and assessed the acoustic contribution of the various components of specific earmuffs. They are reviewed hereafter under subsections addressing the effect of one earmuff component or parameter.

2.2. Effects of the cup

The effects of the mass and the internal volume of the cup have been examined by Berger [11] and Pääkkönen [12]. Berger measured the Real-Ear Attenuation (measurements done on 10 test subjects) of three different earmuffs. Two were commercial HPDs with two different cavity volumes, and one was a damped lead earmuff whose purpose was to investigate the limits of HPD performance. The author figured out that a better attenuation was obtained for the largest cup volume between 125 Hz and 1 kHz because it had the highest mass, while the smallest cup volume gave better performance above 1 kHz because the surface of the cup was reduced. Similar conclusions were drawn by Pääkkönen in [12]. However they also noticed a slight improvement of the attenuation above 1 kHz when the mass of the cup was increased from 64 g to 104 g.

2.3. Effects of the cushion

The seal between the cup and the user’s skin is achieved by two kinds of cushion: foam-filled or liquid-filled. The cushion creates a suspension for the cup. The resonance peak, resulting from the pumping motion of the cup, depends on the mechanical parameters of the skin-cushion system and on the cup mass. In terms of sound attenuation, no difference was observed by Casali and Grenell [13], from 63 Hz to 8 kHz, between both kinds of cushion, when assessing HPDs during moderate work-related activity. While testing different type of foam-filled cushions, Pääkkönen [12] found negligible effects of the foam filling on the noise attenuation in a frequency range from 32 Hz to 8 kHz. To analyze the effect of the transverse cushion vibration, Shaw and Thiessen [14] measured the IL of a baffled earmuff, between 30 to 700 Hz, allowing or not the pumping motion of the cup. They concluded that the sound transmission through the cushion at low frequency is small compared to the ear cup vibration effect (i.e., the pumping motion dominates). Zannin and Gerges [8] investigated the effects on the sound attenuation induced by the cushion of a circumaural earmuff, using an Artificial Test Fixture (ATF). At mid frequency, an improvement was observed when the cushion was removed from the earmuff. The authors claimed that the lightness of the cushion material compared to the cup material was the reason of sound energy leak through the cushion. However, Shaw et al. and Zannin et al. did not measure the sound attenuation of the cushion alone. While validating a FE model of a commercial earmuff coupled to a baffle and an ear simulator, Sgard et al. [15] found better agreement between modeling and experimental results when they neglected the sound transmission through the cushion which indicates a high attenuation for the cushion. Note that this seems in contradiction with Zannin et al. observations. A thorough investigation of the equivalent mechanical parameters of a foam-filled cushion has been made by the authors of the present article on a cushion taken from the earmuff EAR-MODEL-1000 [16]. The sheath stiffness was found to be larger than the inner foam. This study revealed that the effect of the vent holes did not affect the vibration behavior of the equivalent spring-damper system.

2.4. Effects of the headband force

The headband force allows for creating the contact between the cushion’s sheath and the skin. To assess the effect of the headband force on the sound attenuation, Pääkkönen [12] used a headband designed with interchangeable springs to reproduce a force between 6 N and 21 N. An increase of the sound attenuation was observed at low frequency below 250 Hz, and at 4 kHz. Casali and Grenell [13] investigated the effect of the headband force on the sound attenuation for two types of cushions (foam-filled and liquid-filled). Three forces were tested, and results showed a slight improvement of the attenuation when increasing the force from 14.4 N to 16.1 N. However, for a force equal to 24.4 N which is probably at or above the comfort limit, a greater improvement was found at low frequency (below 500 Hz) and at high frequency (above 4 kHz). This improvement was attributed to a better sealing between the cushion and the user’s skin. Zannin and Gerges [8] observed an improvement of the low frequency attenuation when the headband force was increased up to an empirical maximum compression of the cushion. No value of the force was given. The effect of the headband force on the equivalent mechanical parameters of the cushion was studied by the authors of the