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1aNS8. Sound transfer path analysis to model the vibroacoustic behaviour of a commercial earmuff

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Hearing Protection Devices (HPD), such as earmuffs, are widely used to protect workers from noisy environments. Numerical predictive tools can be used to simulate the vibroacoustic behaviour of earmuffs and thus assess their sound attenuation and improve their acoustical design. The present work describes the implementation of a vibroacoustic finite element numerical model of an earmuff coupled to a rigid baffle in the frequency range from 20Hz to 5000Hz. An experimental assessment of the sound transfer paths through each element of the earmuff (cup, cushion, foam lining) using a specific acoustical test bench is first proposed. This analysis is then used to target the right level of model complexity for each component. An experimental validation of the FEM model is then carried out.

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INTRODUCTION

Individual hearing protection remains the short term most used solution to protect workers against noise exposure because of its small cost and its simplicity of implementation. To tackle some issues related to hearing protection, a research project funded by IRSST has started in 2010. The ultimate goal of this research is to develop modeling and experimental tools and methods to better evaluate the objective real world attenuation of HPDs and to help designing more efficient HPDs. A major part of the project is dedicated to the development of individual field attenuation measurement methods and to the measurement of the occlusion effect. Another important part of this work aims at using numerical modeling to achieve an optimal design of a field attenuation measurement set-up developed in the scope of this research project by (i) providing a better understanding of the physics of the ear canal/hearing protector system (ii) helping to interpret experimental results (iii) helping to improve the HPD acoustic design which is often based on empirical procedures.

The scope of this paper is the numerical modeling of the vibroacoustic response of commercial earmuffs. It is commonly made up of a cup filled with sound absorbing material and a cushion of annular shape, which is generally made of foam inserted in a polymeric sheath. The sheath is usually perforated locally with small holes (size of the order of sub millimeter) in order to evacuate air when the earmuff is worn. The earmuff headband allows for the earmuff to stick to the head by applying a static force on the cushion. Past studies showed that the Finite Element Method can be used successfully to predict the vibroacoustic behavior of HPD ((Anwar, 2005), (James, 2006), (Du and Homma, 2009) (Vergara et al., 2002) (Khani et al., 2007) (Sgard et al., 2010)) over a large frequency range. Therefore, this numerical method has been chosen to model an earmuff coupled to an ear simulator.

Several past experimental works focused on the sound transmission through specific earmuff parts provide information regarding the way of modeling each component. To analyze the effect of sound transmission through the cushion, Shaw et al. (Shaw and Thiessen, 1958) measured the insertion loss of a whole earmuff in a configuration where the cushion was alternatively allowed and prevented to move. They found that the sound transmission through the cushion at low frequency is small compared to the pumping motion of the cup. Pääkkönen and Kuronen (Paakkonen, 1992) made objective measurements of insertion loss of helmets and headsets on active military subjects in anechoic rooms using microphones. The main goal was to provide guidelines for product development. They confirmed that (i) the low-frequency attenuation (under 1 kHz) is governed by the pumping motion of the ear cup and (ii) the earcup properties (i.e., volume, material), headband force and foam lining play an important role at high frequency (above 1 kHz). Zannin et al. (Zannin and Gerges, 2006) characterized each earmuff component using their attenuation measured with an Artificial Test Fixture (ATF). They found that increasing headband force increased also attenuation over the frequency range of interest 100 Hz – 8 kHz. They also observed experimentally that foam lining damped the air cavity resonances inside the earmuff. Even though these studies identified the main physical phenomena which govern the sound transmission through earmuffs at low and high frequency (i.e. the pumping motion at low frequency, and sound transmission through the cup at high frequencies), uncertainties of the contribution of the earcup, the cushion and the foam lining remain in middle frequency. It is then proposed to not limit the study in 1/3-band octave, and increase the frequency resolution in order to have a better scope on the vibroacoustic behavior of a earmuff, and how its component govern the vibroacoustic response.

The aim of this work is to provide robust experimental data of the sound transmission through earmuff components with and without vibroacoustic couplings between the various components in order to better understand the vibroacoustic behavior of an earmuff and hence to target the right level of modeling of each of its components. The work proposed in this paper is the continuation of the experimental studies of Pääkkönen and Kuronen (Paakkonen, 1992) and Zannin et al. (Zannin and Gerges, 2006). However, the proposed objective measurement method is carried out in controlled laboratory conditions to increase the maximum measurable attenuation and decrease measurement variability. The decoupling between earmuff components is also improved to investigate separately the effect of the cushion, earcup, foam lining and pumping motion of the earcup. These measurements are indeed very delicate because they require controlling the parasitic transmission paths (flanking paths, leaks) and because the insertion loss of the components is pretty high. The experimental setup has thus been designed with great care. Narrowband measurements are carried out in an anechoic room from 20 Hz to 5000Hz, using five samples of each earmuff component, so that a statistical analysis can be performed on data results. Great care is taken to choose the right way to fix samples onto the baffle, to avoid leaks, and to control the headband force when the pumping motion of the cushion is allowed. This experimental analysis is going to be used (1) to select the modeling refinement of each earmuff component to build a FE model of the complete earmuff and (2) to validate the complete numerical model. The comparison between the simulation and the experimental data will be presented during the conference.

The paper is organized as follows. First the acoustic test bench used to analyze the different pathways through each earmuff components (cup, cushion, foam lining) is described. Then the results of this analysis are presented and discussed. Finally, a summary of the main conclusions is given.

EXPERIMENTAL METHOD

Acoustic test bench

The assessment of the transfer paths through each earmuff's component is carried out in a semi-anechoic room whose one side-wall has been modified by replacing foam wedges with a gypsum double wall. A one foot square opening is cut in the center of the first wall to fit a steel plate. This plate, together with the front gypsum wall, constitute a rigid baffle (see Fig1(a)). To avoid frequency resonances of the first gypsum wall to be transmitted to the steel plate, the steel plate is mounted on a frame which is decoupled from the front gypsum wall.

The steel part of the baffle is instrumented with two flush mounted microphones. A ¼-inch BK multifield microphone type 4961, with sensitivity around 65mV/Pa, is used to measure the SPL (sound pressure level) under the HPD and is called the "measurement microphone". The second microphone, (PCB piezotronic 130E20) is also inserted into the baffle at a distance of around 15cm from the measurement microphone and is used as a "reference microphone" (see Fig. 1(b)). These two microphones are used to quantify the earmuff attenuation as explained in next section.

A loudspeaker mounted in a duct is used as a monopole sound source. It is placed at 1m from the setup, to keep a high sound pressure level, typically between 85 and 90 dB, over the frequency range tested (20 Hz to 6 kHz). A pink noise, generated by a Larson Davis SRC20, is used as excitation to ensure that low frequencies are reinforced, (Sweep noise excitation was also tested, but no improvement was found). The sound level signal was adjusted using a 1/3-octave band equalizer. Data acquisition was made using the Brüel&Kjaer Pulse analyzer, release 16.1.0.

As mentioned earlier, the measurements to identify the sound transmission pathways are very delicate. Special attention had to be given to the design of the test bench in order to obtain accurate and reliable measurements. Firstly, the test bench includes a special device to reproduce the headband force applied on the earmuff. It has been designed to be acoustically transparent and to avoid parasitic vibrations which could pollute the measurements. Secondly the reference microphone has been flush mounted into the steel plate instead of being located close to the baffle, in order to improve the quality of the signal at high frequencies. Finally, the main difficulty was to find an acoustic sealant to avoid air leakages between interfaces. If petroleum jelly (Vaseline) was found a good candidate when testing samples without pumping motion, it was causing some artifacts at low frequency, when the pumping motion was allowed. Because of the greased contact between the cushion and the baffle, the frequency resonance was not well reproduced (the peak was shifted at higher frequency, with a smaller amplitude). Various types of silicone were then tested (MULCO Zip Seal'n peal, GE Silicone I) but they did not prove to be good candidates for this kind of measurements (repeatability problems, shift in time). The sealant which provided the best results is non-hardening synthetic butyl rubber sealant (MONO acoustical sealant).

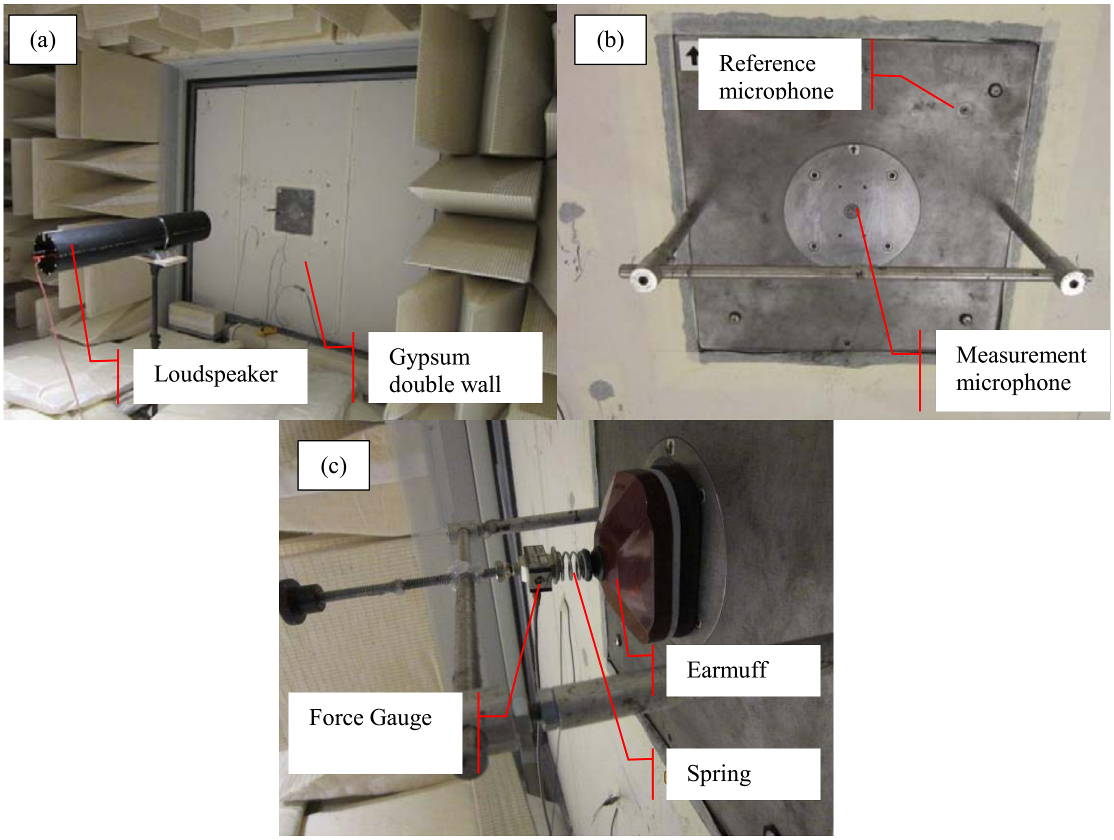

FIGURE 1. Experimental setup: (a) Overall view in the anechoic chamber, (b), Instrumented rigid steel plate, (c) Sample mounted on the baffle using the special device to reproduce the headband force

Measurement configurations and material

The commercial earmuff (E-A-R model 1000) used in this work is presented in Fig2. It is an assembly of five parts: an earcup, a foam lining, a backplate press-fitted to the earcup, a cushion which is glued to the backplate, and a ball joint to clamp the earcup to the headband.

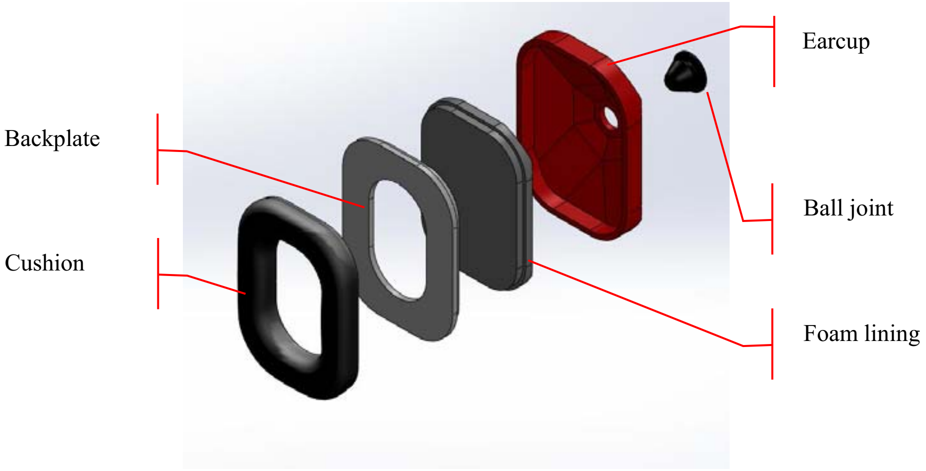

FIGURE 2. Components of the studied earmuff

Seven configurations are considered to investigate which components or physical mechanisms contribute the most to the sound pressure level inside the earmuff. The configurations are presented in Figure 3 and summarized in Table 1. In order to decouple the contributions related to the earcup and the cushion, two complementary parts have been built:

(1) A "lead cushion" whose shape is identical to the earmuff's cushion, and a steel plate which is used as an earcup. The lead cushion has a very high sound insulation and allows one to block the sound transmission through its walls.
(2) The 3/8in thick steel plate was designed to be soundproof in the frequency range of the study.

Configuration 1 shown in Fig. 3 is a "rigid" earmuff (also called "Metal cup" by Zannin et al. (Zannin and Gerges, 2006)) used to estimate the maximum attenuation measurable with the proposed setup.

In configuration 2, the steel plate is placed on top of the cushion and screwed onto the baffle using internal spacers to block the pumping motion; the sole sound transmission through the cushion walls is then investigated.

In configuration 3, the plate motion is allowed and an external static force is applied at the plate center via a spring attached to a force gauge to reproduce the earmuff headband force; the pumping motion coupled to the transmission through the cushion walls is investigated.

Configuration 4 corresponds to the case of the real earcup coupled to the lead cushion. This allows one to isolate the sound transmission through the sole earcup.

Configuration 5 is identical to configuration 4 but a foam lining inside the earcup is added.

Configuration 6 is identical to configuration 4 but the lead cushion has been replaced with the EAR1000 cushion.

Finally configuration 7 corresponds to the complete earmuff. The external static force is set to 11.5N, which is a classic value of headband force encountered when earmuffs are tested on a standardized Artificial Test Fixture.

TABLE 1. Main configurations of the experiments to characterize the vibroacoustic behavior of each part of the earmuff.

#	Configuration	Earcup	Cushion	Pumping motion	# samples	Acq/sample
1	Maximum achievable	Steel plate	Lead cushion	No	1	1
2	Cushion without pumping motion	Steel plate	EAR1000 cushion	No	5	3
3	Cushion with pumping motion	Steel plate	EAR1000 cushion	Yes	5	3
4	Earcup without foam lining	EAR1000 earcup	Lead cushion	No	5	3
5	Foam lining inside the earcup	EAR1000 earcup + foam lining	Lead cushion	No	5	3
6	Earmuff without foam lining	EAR1000 earcup	EAR1000 cushion	Yes	5	3
7	Complete earmuff	EAR1000 earcup + foam lining	EAR1000 cushion	Yes	5	3

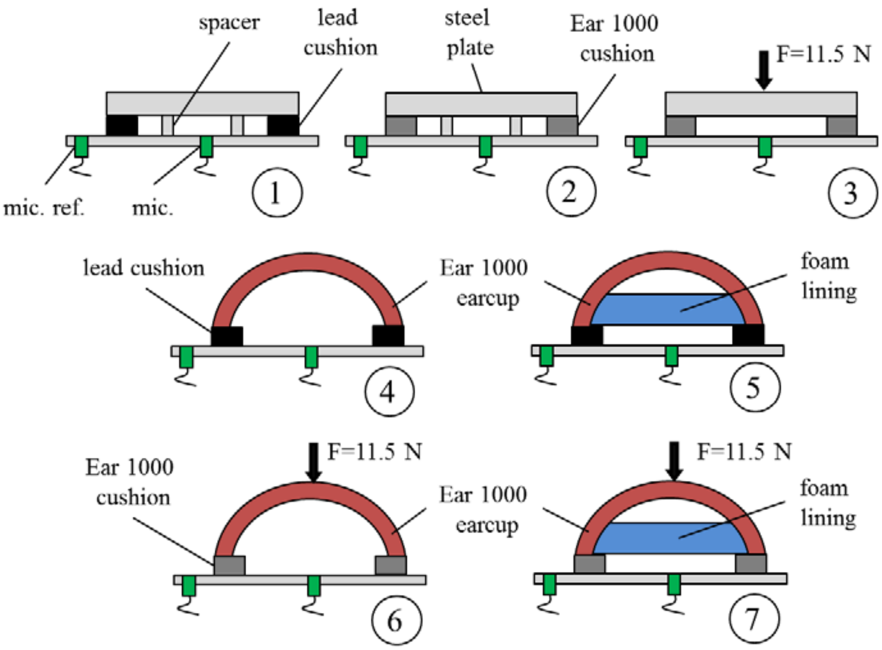

FIGURE 3. Configurations of the experiments to characterize the vibroacoustic behavior of each part of the earmuff.

The Insertion Loss (IL) is used to characterize the sound insulation efficiency of all configurations presented in Table 1. It is generally defined as the difference of the sound pressure levels captured by the measurement microphone with $L_p{}^+$and without $L_p{}^-$ the component to be tested:

$$IL = L_p^- - L_p^+. \tag{1}$$

Alternatively, the IL can be calculated using the transfer function $h_1 = G_{xy}/G_{xx}$ between the measurement microphone x and the reference microphone y. Advantages of the use of the transfer function were: (1) to normalize each measurements, that can be later compared to others, (2) to verify the good working of the measurement in real time (as the transfer function of the flush mounted microphones is an estimator of the insertion loss), (3) to achieve more accurate results by reducing the electronic noise (when using a less accurate data acquisition system)

$$IL = 20.\log_{10}\left(h_1^-\right) - 20.\log_{10}\left(h_1^+\right). \tag{2}$$

For each configuration, i components are tested j times, and n acquisitions are run. In addition, m acquisitions are done without any samples. An average Insertion Loss can then be computed together with a confidence interval.

RESULTS AND DISCUSSION

The Insertion Loss of the rigid earmuff (i.e., configuration 1) is plotted Figure 4, and represents the limit of the experimental setup. It is shown that IL is higher than 60dB in the whole frequency range, as recommended by Berger in the case of ATF measurements (Berger, 1986). It is even higher than 70 dB for frequencies above 700 Hz.

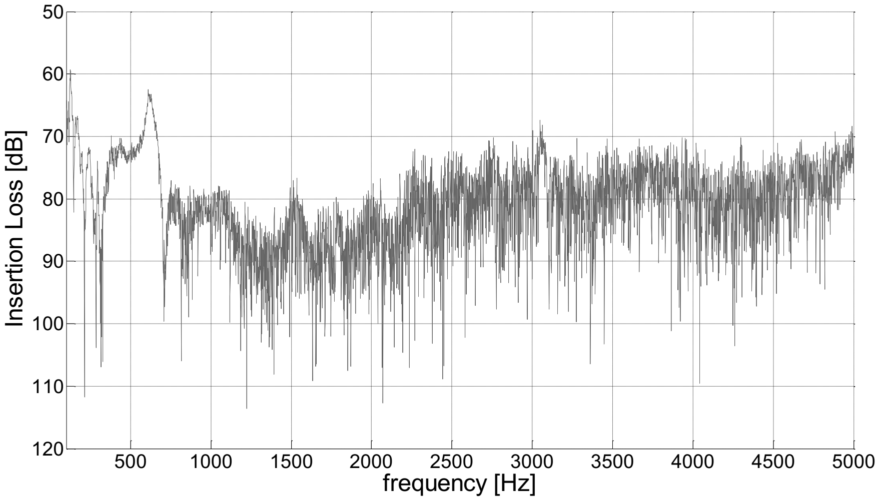

FIGURE 4. Insertion Loss of the rigid earmuff (i.e., lead cushion and steel plate, configuration 1)

The insertion Loss of configurations 2, 3, 4 and 5 are plotted in Figure 5. It is seen that the IL of the cushion without pumping motion (configuration 2, black curve in Fig. 5) is high, and remains relatively flat over the test frequency range. When the pumping motion is allowed (configuration 3, brown curve in Fig. 5), the IL decreases dramatically at low frequency (up to 800 Hz), and is governed by the mass/spring resonance of the steel plate/cushion +air cavity system.

Above 800 Hz the IL measured for configurations 2 and 3 are very close to each other (they are even superimposed above 2.5 kHz); the pumping motion is negligible. It is worth noting that a heavy steel plate has been used in configuration 3; the spring/mass resonance frequency is thus shifted toward low frequencies compared to the real HPD made of a light earcup.

The earcup with or without foam lining (compare green and red curves in Fig. 5) shows the lower IL between 1.6 kHz and 2.6 kHz and above 3.6 kHz; the earcup is the main sound path.

Finally, both the cushion and the earcup contribute similarly to the IL between 2.6 kHz and 3.6 kHz. As expected, the foam lining damped the acoustic resonance inside the cavity around 4.1 kHz

The IL of the real earmuff with the pumping motion and without the foam lining is presented Figure 6 (i.e, configuration 6, see blue curve in Fig. 6). The effect of the pumping motion can be investigated in more details by comparing configurations 3 and 6 (see brown and blue curves respectively). Both configurations present a minimum of attenuation at the mass/spring resonance frequency followed by a maximum of attenuation (see black points and black squares in Fig. 6). The minimums and maximums of both configurations are shifted in frequency since the mass on top of the cushion is different. It is interesting to note that the amplitude of the maximum IL in the case of the real earmuff without foam lining (configuration 6) is higher than the attenuation provided by all components (compare blue, black and red curves around 1 kHz). This maximum is the result of a vibratory coupling between the cushion and the earcup which minimize the sound pressure measured on the baffle. Similar comments can be drawn at the frequency of 2.3 kHz for which the attenuation of the complete earmuff (blue curve) is higher than the one of the other components. In this case, a structural vibration of the earcup (detected by a minimum attenuation of the earcup, see red curve in Fig. 6) should be perturbated by the flexible boundary condition due to the presence of the cushion.

This works confirms that (i) at low frequencies, from 20 Hz to 800 Hz, the vibroacoustic behavior of the complete earmuff is governed by the pumping motion of the earcup+cushion, and the sound transmission through the cushion is negligible; (ii) in the frequency band 1,6 kHz to 2,6 kHz and above 3,6 kHz, the earcup is the main sound path ; (iii) the foam lining has a strong influence above 3,6 kHz. However, this study also shown that the transmission through the cushion can have a non-negligible influence between 800 Hz and 1.6 kHz (compare black and brown curves in Fig. 5) and between 2.6 kHz and 3.6 kHz (compare black, red and green curves in Fig. 5).In these frequency bands the IL provided by the cushion is similar to the one provided by the cup with or without pumping motion.

Consequently, to develop a FE model it is required to model adequately (i) the sound path through the earcup, and the foam lining, which can be modeled using solid or shell elements (ii) the low frequency mass-spring effect induced by the earcup-cushion-cavity system which can be modeled as boundary condition, using a damped spring foundation model, and (iii) the transmission through the cushion at medium frequencies. Future works will thus also focus on the modeling of the cushion to determine if a simple spring model is suitable or if a more complex model is required.

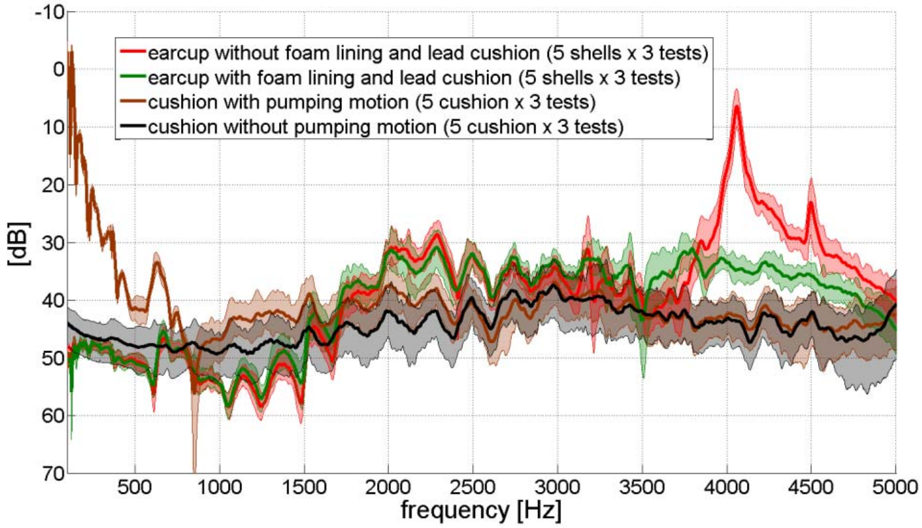

FIGURE 5. Insertion Loss (Average) of each component of the earmuff E-A-R model 1000: configuration 2, cushion and steel plate without pumping motion (black); configuration 3, cushion and steel plate with pumping motion (brown); configuration 4, cup and lead cushion without foam lining (red); configuration 5, cup and lead cushion with foam lining (green). Average experimental results are plotted together by their confidence interval at 99%.

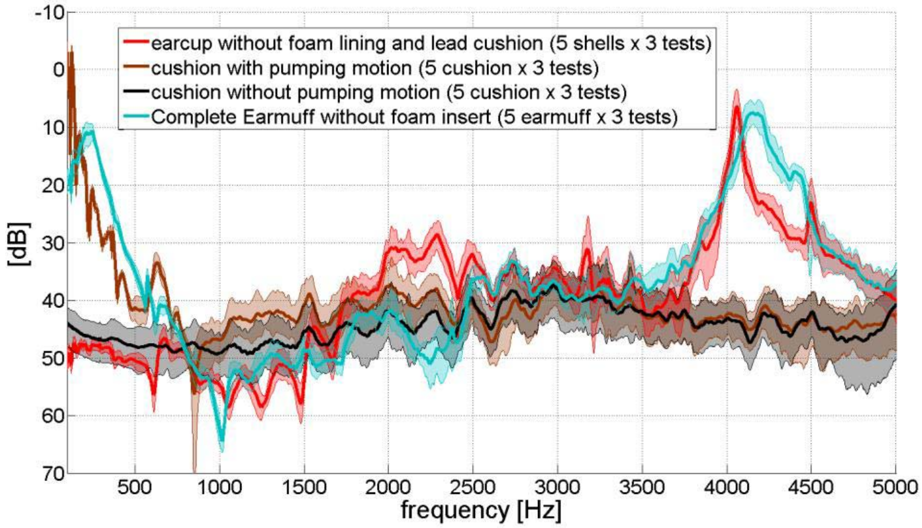

FIGURE 6. Insertion Loss (Average) of the earmuff E-A-R model 1000 without foam lining, and its components: configuration 2, cushion and steel plate without pumping motion (black); configuration 3, cushion and steel plate with pumping motion (brown); configuration 4, cup and lead cushion without foam lining (red) ; configuration 6, complete earmuff without foam lining. Average experimental results are plotted together by their confidence interval at 99%.

CONCLUSION

In this paper, an experimental transfer path analysis through each component (cushion, earcup, foam lining) of a commercial earmuff (EAR 1000) in controlled laboratory conditions has been carried out. The purpose of this analysis is to guide the development of a FEM model of the complete earmuff and justify the choice of the model refinement for each earmuff component especially the earcup and the cushion. An original experimental set-up and a methodology have been proposed to carry out accurate Insertion Loss measurements which allow for a rigorous separation of the earcup, and cushion, pumping motion and foam lining contributions to the sound pressure level under the earmuff.

Compared to previous studies, highest and more accurate insertion loss levels were obtained, resulting from the specific design of the test bench, as well as the new computation of the insertion loss with the use of transfer functions, and the better control of the air leakages. With narrowband measurements, it was possible to specify different zones in the insertion loss of the complete earmuff, where each part of the earmuff governs the vibroacoustic behaviour.

The measurements show that the vibroacoustic behavior of the complete earmuff is governed from 20 Hz to 800 Hz by the pumping motion of the earcup+cushion, rather than the sound transmission through the cushion. From 1,6 kHz to 2,6 kHz and above 3600 Hz up to 5000Hz, the response is controlled by the sound path through the earcup. The main issue remains the frequency bands 800 Hz to 1600 Hz and 2,6Kz to 3,6 kHz, where coupling between the cushion and the earcup and between the earcup and the foam lining appear. If a good choice of FE model for the complete earmuff would be based on solid or shell elements for the earcup, equivalent fluid or poroelastic elements for the foam lining, investigations need to be done on the cushion model which should be able to reproduce the observed behavior on the whole frequency range.

Based on this analysis, such a FE model is going to be developed and experimental validation results will be presented during the conference.

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