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Technical Notes

Earmuff Noise Leakage Measurements and Evaluation

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This paper reports the quantitative effect of leakage on the noise attenuation of earmuff hearing protectors. The technology used in this study to measure the noise leakage is considered to be a new contribution to this topic. An array of sensors placed between an earmuff and a dummy human head or flat surface was used to measure the contact area. Areas of no contact are considered as the leakage elements. Eight earmuffs varying from high quality/high cost to low quality/low cost were tested, the leakage areas were measured and the reduction in the noise attenuation due to leakage was calculated.

Keywords: earmuffs.

1. Introduction

The performance of circumaural earmuffs plateaued more than 40 years ago (Shaw, Thiessen, 1958) and since then further developments have not changed the maximum achievable noise reduction by a significant amount. A large number of publications can be found on noise attenuation measurements, developing standards and applications, but very few are available on earmuff noise leakage.

For an open ear (without earmuff) the dominant noise propagation path is through the propagation of sound waves in air to the eardrum at the end of the ear canal. However, when an earmuff is worn, five distinct sound paths can be identified, as shown in Fig. 1.

1. **Bone and tissue conduction:** Acoustic energy can be transmitted through the skull bone and tissue (flank or bypass) which is approximately 40–50 dB below the level of air-conducted sound passing through the open ear canal. This imposes the upper limit of noise attenuation of the earmuff (Berger, 2000). Most earmuffs will provide attenuation approaching that of bone conduction, approximately 40 dB, for frequencies above 2,000 Hz.
2. **Non-contact area air leak:** Sound energy is higher outside the earmuff and lower inside. Sound energy propagates from higher to lower energy. Therefore, this leakage path is very important and will be discussed in greater detail below.
3. **Vibration of earmuff:** An earmuff can vibrate as a single degree of freedom mass/spring system with resonance in the low frequency range. This action limits the low frequency band (<125 Hz) noise attenuation.
4. **Ear cup transmission:** The ear cup is generally made of plastic with a thickness of around 1 to 3 mm

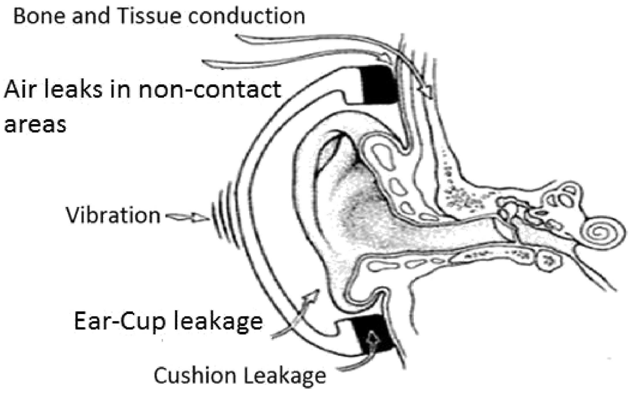

Fig. 1. Five paths of noise leakage.

and this is sufficient to provide the necessary noise attenuation of the earmuff.

5. **Cushion transmission:** The cushion is generally made of soft and light materials (than Ear cup) to provide comfort for the user and therefore is a weak path for noise leakage. Work carried out by Zannin (Zannin, Gerges, 2006) reported that if the cushion is removed an increase in the noise attenuation of around 10dB is observed.This represents a challenge for earmuff designers seeking materials for the cushion to minimize this pathway and provide sufficient comfort.

Figure 2 shows examples of a well-fitted earmuff with a good seal all around the outer ear and an earmuff with a leak underneath the cushion in the non-contact areas.

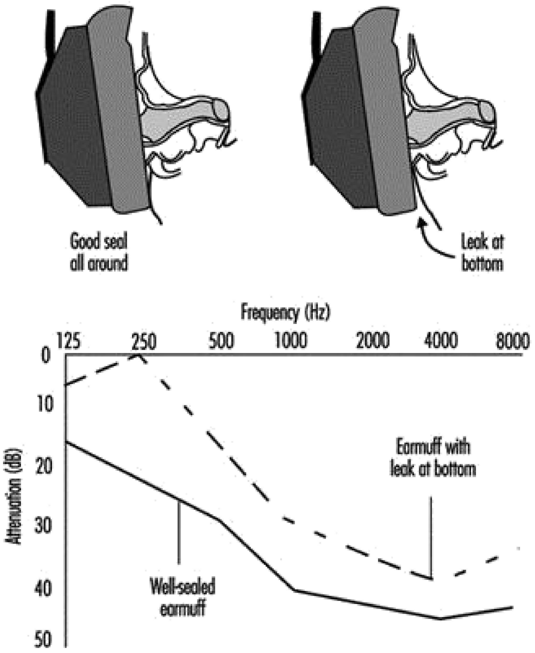

Fig. 2. Noise attenuation of well-fitted and poorly-fitted earmuffs (Berger *et al.*, 2011).

Noise leakage reduces the attenuation and can be due to several parameters related to users:

1. **Wear and tear.** The lifetime of an earmuff is limited since the ear muff headbands may lose their tension, the ear cups may no longer fit securely, and the cushions may deteriorate with age, becoming brittle and no longer conforming to the head. These factors result in the loosening of the fit of the hearing protectors and lead to noise leakage.
2. **Using improper sizing.** It is important that the manufacturers offer different sizes and that the user selects the correct option. Users generally select a small plug (too loose) which is more comfortable, but leaves a gap for noise leakage. On the other hand a large plug may be too tight, which causes discomfort. Some users have ears of different sizes and they should use different sized plugs on the left and right ears.
3. **Compatibility of hearing protector with other Personal protection equipment:** Helmets and safety glasses are commonly used simultaneous with hearing protectors and the arms of safety glasses can break the earmuff seal resulting in leakage. The earmuff and helmet should be designed to be used simultaneous. Cushion materials usually have low noise transmission loss and therefore they are a weak path for noise leakage. Cushions are important for comfort and therefore should be optimized. Long hair, a beard and earrings can all break the seal of earmuffs.
4. **Wrong insertion.** Users generally insert the hearing protector for comfort and not for noise attenuation. Workers often fit hearing protectors loosely since they are aware that they will need to wear them for the whole working shift and this results in leakage through air gaps.
5. **Communication.** Workers sometimes need to communication with each other or to hear important warning signals or the machine sounds. With the use of earmuffs the perception of sound is reduced and therefore workers tend to remove their hearing protectors or loosen them so that they can hear certain sounds in the environment around them. In addition,workers who already have noise-induced hearing loss will experience greater difficult over time in hearing the desired sounds when they wear protectors, giving them further reason to loosen their protectors and let them leak. The loosening or partial removal of hearing protector can lead to the development of attenuation leaks.
6. **User modification**. Muffs may be modified by opening the headband. Or holes can be drilled to release the pressure on the ear. In this case considerable attenuation will be lost.

The earmuff cushion plays an important role in relation to the overall earmuff characteristics. It has two important objectives: (i) to provide comfort; and (ii) to reduce the leakage and transmission of noise to the inside of the earmuff cup. However, if the cushion materials have poor acoustics isolation properties, the noise attenuation will be reduced. Zannin and Gerges (2006) showed that low sound attenuation by an earmuff at low frequencies can be due to the contact between the cushion and the human face, vibration of the cup surface and the presence of low density materials in the cushion. When the cushion was removed there was an improvement in the noise attenuation of around 10 dB. Since the cushion is the element responsible for the comfort associated with the contact between the cup and human face and is an indispensable element, effort should be concentrated on finding cushion materials which provide less leakage and higher noise isolation. At high frequencies, the foam lining material inside the cushion is responsible for reducing the acoustic resonance frequencies of the cup air volume. The cushion leakage location was not identified in the above-cited paper (Zannin, Gerges, 2006).

Paurobally and Pan (2000) created a low frequency model for a near cup on a cushion as a simple vibration system and reported that leakage introduces a new resonance at very low frequencies and also shifts the first resonance to a slightly higher value. It was noted that above the resonance frequency the sound attenuation of the device decreased in the presence of leakage. The authors of the above-cited paper did not identify the leakage location or quantify the difference in noise attenuation due to leakage.

Noise transmission from one media to another is very sensitive to any opening at the interface between the two media. For example, if the earmuff cushion surface area is $A = 0.05$ [m^2] and the cushion wall sound transmission loss is TL [dB] $= 30$ dB, corresponding to sound transmission coefficient of $\alpha = 10^{-3}$. If the cushion has a small opening of 1% of the cushion area S [m^2] $= 0.0005$ [m^2] (an opening has a sound transmission coefficient of unity), then the overall transmission loss is given by (Reynolds, 1981).

The overall TL with hole = 10 log [(total area of cushion and hole)/(cushion area × α + hole area $S\times 1$)] $= 10\log[(A+S)/(A\times\alpha+S\times 1)]$
$= 10\log\,[0.0505/(0.05\times 10^{-3} + 0.0005\times 1)]$
$= 10\log\,[0.0505/0.00055] = 10\log 91.818 = 20$ dB.

This means that for 1% of open area the transmission loss is reduced from 30 dB to 20 dB.

Therefore, small openings can considerably reduce the noise attenuation. This is important in relation to earmuff hearing protectors, which, in general, do not provide a continuous seal around the ear and there will be some areas with no contact.

This paper presents a new technique for identifying the leakage location and leakage area and quantifies the reduction in the noise attenuation due to leakage.

This paper identifies the contact pressure between the earmuff and the surface of a human face or a flat surface and quantifies the leakage and loss in noise attenuation. This was carried out by taking measurements which were used to produce a pressure contact map employing an array of over one thousand sensors. Therefore, a good earmuff cushion should have a soft surface in contact with the human face in order to provide comfortable contact with minimal leakage, and also cushion with good sound isolation.

2. Measurement system

Previous publication by the same main author dealt with comfort evaluation at applied acoustics 2012 (Gerges, 2012) and ICA 2010 (Gerges *et al.*, 2014). This comfort work published was carried out using a measurement system composed of 1960 array de senores mad from rigid plastic as shown in Fig. 5. This rigid plastic gives false signal when bend the ear surfaces. Therefore a new measurement system is developed in this paper uses a new measurement system both for comfort and leakage evaluation. The 1024 sensor array is in flexible mat which is glued rigidly on the human dummy head and on flat surface (see Figs. 3 and 4).

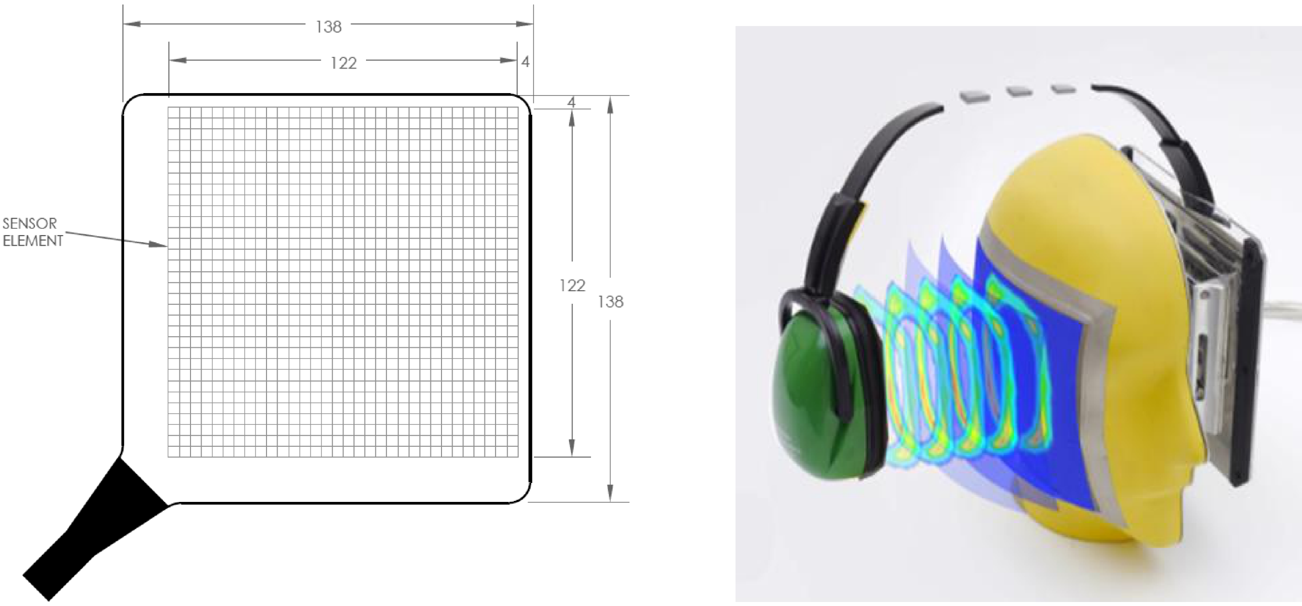

Fig. 3. Conformable tactile sensor elements (manufactured by PPS), one on each side (see Fig. 2). Permanent fixed sensors. Each side has 1024 sensors over an area of 3.8×3.8 mm.

Fig. 4. Variable width measurement systems with flat surface on one side and half dummy human head on the other side.

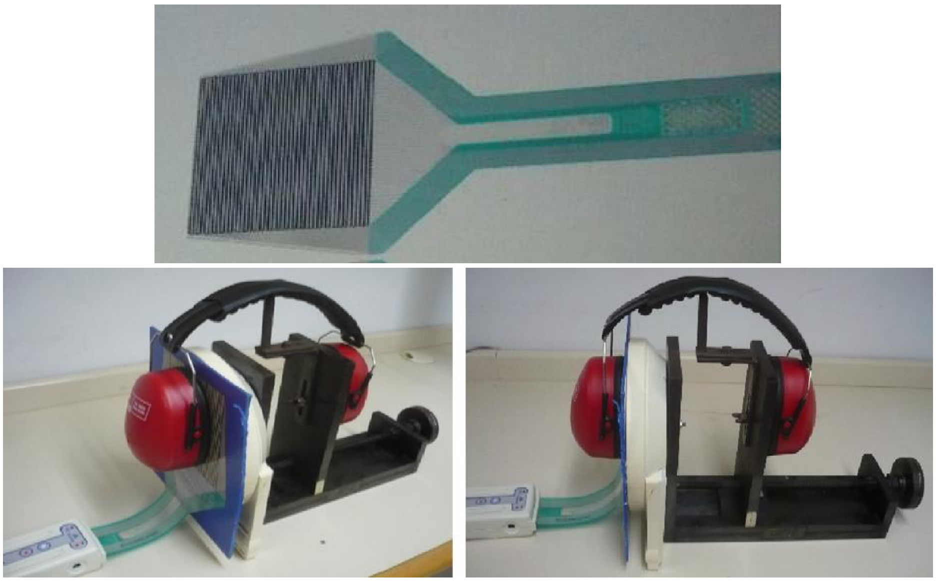

Fig. 5. TEKSCAN SENSOR ARRAY (upper figure) and measuring contact pressure on flat surfaces (lower figures).

*2.1. PPS System (*Gerges *et al., 2014)*

Highly sensitive conformable tactile capacitive sensors (Gerges, 2012; Gerges *et al.*, 2014) with threshold down to pressures of less than 2 [KPa] were mounted onto the measurement system (Figs. 3 and 4). The sensor surface is 122×122 mm with 32×32 sensors and each sensor has an area of 3.8×3.8 mm. A fixture with variable width was constructed with a flat surface on one side and a half dummy human head on the other side, as shown in Fig. 3. The half dummy head satisfies the requirements detailed in the ANSI S3.36 standard (ANSI, 1985). The open width of the earmuff was adjusted to 145±1 mm as recommended in ANSI S12.6-2008 (2008) for the measurement of the headband force.

Figure 4 shows the measurement system, where one side is a flat surface and the other side is a half dummy human head (constructed according to (ANSI, 1985)). Each side has an array of 1024 sensors to measure the contact pressure.

2.2. A TEKSCAN I

Scan Lite Enhanced system, type 5101 (Gerges, 2012), with 1936 pressure resistive sensors (see Fig. 5) was used. Also, a software program was developed to transform the color map pictures into numerical values to calculate the areas of no contact. The TEKSCAN sensor array is difficult to use for measurements taken on curved surfaces, like those of a dummy human head, since it is made from hard plastic and when it bends it gives false signals. Thus, it should be used only in flat surfaces.

Figure 6 shows typical results for the measurements taken on a flat surface and on the dummy head, where

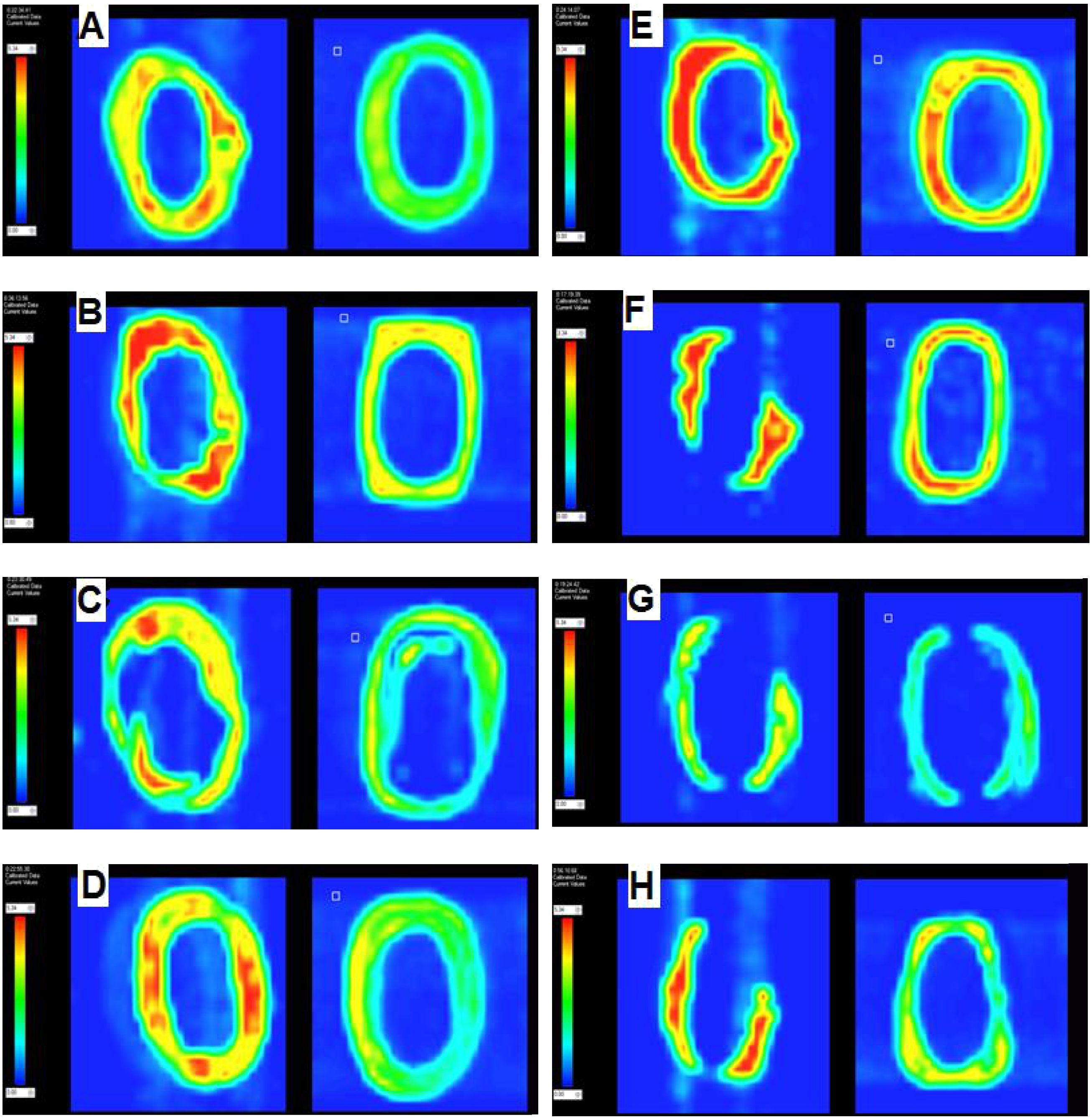

Fig. 6. Contact pressure mapsforthe eight earmuffs A to H (left figures for dummy head and right figures for flat surface), showing the contact areas and non-contact areas where leakage could occur.

areas with good contact (case A) and no contact area (as shown in cases F, G and H for half dummy head) can reveal the potential for noise leakage.

3. Measurements of leakage area

The non-contact areas measured by the TECKSCAN or PPS sensor array are the leakage areas.

The measurement of earmuff sound attenuation reduction caused by leakage is made by measuring the contact area and non contact area between the earmuff and dummy human dead and flat surface.

Measurements were carried out for eight types of earmuffs (A, B, C, D, E, F, G and H). Three samples of each type were subject to three measurements each and the average results considered. Figure 6 shows the contact pressure maps for the eight earmuffs. Some earmuffs show greater homogeneity in the distribution of the contact pressure than others. Also, some earmuffs show no contacts at all in certain areas, where noise leakage may occur.

There appears to be a lower degree of noise leakage for the flat surface compared with the dummy human head, which according to (Gerges *et al.*, 2008) leads to the attenuation measured on an Artificial Text Fixture ATF always being higher than that measured on a dummy head or human subject.

4. Leakage evaluation

For each of the eight earmuffs tested, the maximum contact area of the cushion is measured, with an open distance of 145±1 mm between the cushion and the test surface (as recommended by ANSI S12.6-2008 (2008)). Table 1 shows the contact area in which the measurements were taken. The leakage areas are shown in Fig. 6. Table 1 provides details on the cup area measured for each earmuff, non-contact areas measured on the contact pressure maps in Fig. 6, and the reduction in the noise attenuation. The non-contact area is calculated by multiplying the non-contact arc length by the height of the air gap which is around 2.5 mm.

Table 1. Noise attenuation reduction due to leakage.

	Dummy Head			
	Cup area [cm^2]	Non-contact area [m^2]	% Open Area = Non-contact area/Cup area	Noise attenuation reduction [dB]
A to E			NO Leakage	
F	163	3	3/163 = 1.8 %	**4.5**
G	111	2	2/111 = 1.11%	**4.4**
H	142	2.80	2.8/142 = 1.4%	**4.7**

It can be observed in Table 1 that three of the eight earmuffs appear to have areas of no contact in the case of the dummy head (F, G and H). These areas of no contact are not very big in relation to the total cushion areas and therefore the reduction in the noise attenuation is in the order of 5dB.

5. Conclusions and future requirements

It is possible to identify and measure the noise leakage of an earmuff on a flat surface or dummy human head and quantify the subsequent loss of noise attenuation. This can be carried out by using an array of contact pressure sensors (capacitive or resistive). The sensor array needs to be able to measure the contact pressure down to a value near to zero [Pa], but up to about 2 [KPa] can be tolerated. This type of contact array sensor needs to be further developed in order to measure very lower contact pressure and also provide accurate and repeatable results. Two measurement systems were used, a TEKSCAN system which has non-flexible sensors, which is not recommended for curved surface like dummy head, and a PPS system which has the sensors glued onto the flat or dummy head surfaces. The results obtained from the PPS system show that the presence of leakage areas reduced the noise attenuation by up to 5 dB, since these areas are not very large compared with the total surface area of the earmuff cup. The results obtained in our previous studies (Zannin, Gerges, 2006) showed that eliminating the cushion completely can provide higher noise attenuation which may be of the order of 10 dB. Therefore, the noise isolation properties of the cushion material are an important factor. Hence, in some cases, earmuffs with a very thin cushion area can provide greater noise attenuation. The challenge is to design a cushion comprised of materials which allow high noise isolation and also provide the soft contact required for comfort (Gerges, 2013; Williams, 2007; Hsu *et al.*, 2004; Arezes, Miguel, 2002; Arezes, 1998).

Acknowledgments

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