When measuring the insertion loss of a hearing protection device (HPD) with an acoustical test fixture (ATF), the measured insertion loss can be limited by the self-insertion loss (SIL) of the ATF. The SIL is impacted by any pathways that allow acoustic energy to reach the ATF ear simulator microphones via a route other than through the HPD being measured. Standards that specify the use of an ATF for HPD measurements (such as ANSI/ASA S12.42 or ISO 4869-3) include minimum requirements for the SIL of the ATF, as one component in ensuring the validity of insertion loss measurements made on HPD samples. Traditionally, SIL has been measured with any artificial flesh simulations removed from the ATF and with the ear simulator microphones blocked by metal plugs or isolation caps. Such measurements may not be representative of the SIL obtainable when the ATF is configured for HPD measurements. We propose a method for measuring the ATF SIL with all flesh simulations in place and as configured for HPD measurements and present data measured on several commercially available ATFs. We also propose insertion loss limits to be met by ATFs when measured with this method, in the hopes that such limits will be useful to future revisions to HPD measurement standards using ATFs.

Keywords: hearing protection, insertion loss, acoustical test fixtures

1. Introduction

The real-ear attenuation at threshold (REAT) procedure has long been the “gold standard” method to measure the attenuation provided by hearing protection devices (HPDs). The REAT method is based on measuring the hearing thresholds of human listeners, with (occluded ears) and without (open ears) an HPD in place. The difference between occluded- and open-ear hearing thresholds at each test frequency is defined as the HPD attenuation (see, for example, ANSI/ASA S12.6, Ref. [1]). This method captures
many important aspects of HPD performance when used by humans, such as the fit of the device on real ears and the limits to attenuation due to the effects of bone conduction [2].

Acoustical test fixtures (ATFs) provide an objective alternative to REAT measurements, especially useful for testing at high sound pressure levels that would be hazardous to human listeners, quality control, research and development, or similar purposes. An ATF is an artificial head simulation, constructed with microphones in the place of eardrums. Some ATFs also incorporate artificial flesh simulations and heaters in the earcanals or circumaural regions to better simulate the environment HPDs will encounter when in use on human ears. When used to measure the insertion loss (IL) of an HPD, the ATF is placed in a sound field and sound pressure levels at its ear simulator microphones are recorded. The IL is defined as the difference in measured sound pressure levels between open (no HPD) and occluded (HPD fitted) ears on the ATF. This technique is standardized in ANSI/ASA S12.42 and ISO 4869-3, for example [3, 4]. IL measurements tend to be more repeatable than REAT measurements; however, they may not be representative of the attenuation attainable by human wearers of the HPD. In addition, poorly constructed or otherwise unsuitable ATFs may produce inaccurate IL measurements [2].

One important consideration in the design and manufacture of ATFs is the maximum possible IL measurable with the ATF, termed its self-insertion loss (SIL). During an occluded-ear measurement, acoustic energy may reach the ear simulator microphones of the ATF after traveling either through the HPD under test or through flanking pathways in the ATF that conduct the sound around the HPD. If the amount of acoustic energy leaking through the flanking pathways of the ATF is greater than the energy propagating through the HPD, the measured IL will be reduced. Therefore, to maximize the SIL of the ATF, any flanking pathways should be minimized.

Standards for HPD measurements using an ATF typically include minimum limits for SIL, to help ensure that the measurements do not underestimate the attenuation of the HPD tested. Traditionally, any circumaural or earcanal flesh simulations are removed when verifying these requirements. For example, the ATF specifications of ANSI/ASA S12.42-2010 require a minimum SIL of 60 dB at frequencies from 80 Hz to 12.5 kHz, measured without the ATF’s flesh simulation and using a “suitable isolation cup or plug” [3].

When used for IL measurements on HPD samples, however, the ATF has its flesh simulations in place. The presence of the flesh simulations may introduce flanking paths around the HPD under test that were not accounted for during the SIL qualification. In this case, measurements on the ATF may underestimate the IL of tested HPDs, even though the SIL requirements were met.

The remainder of this paper reviews the traditional SIL measurement paradigm and presents a method to estimate the SIL of an ATF as used for HPD measurements, with flesh simulations present. Data measured on several commercially available ATFs are presented. Minimum requirements for the SIL measured with this procedure are proposed. ATFs meeting these proposed limits should yield more reliable HPD IL measurements that are not restricted by the insertion loss of the test fixture itself.

2. Methods

This study is conducted using several samples of two commercially available ATFs. Both were designed to meet the requirements of the ANSI/ASA S12.42-2010 standard. The GRAS 45CB ATF, manufactured by GRAS Sound & Vibration, is pictured in Fig. 1(a). The ISL-B ATF, made by the French-German Research Institute of Saint-Louis (ISL), is shown in Fig. 1(b).
2.1 Insertion loss measurements

Insertion loss measurements were made using a quasi-diffuse sound field with a broadband pink noise stimulus presented at an overall sound pressure level (SPL) of 120 dB. The ATF under test was placed at the reference point of the sound field. The ATF microphone outputs were connected to a National Instruments-based data acquisition system, which measured the one-third-octave band SPLs generated at the ATF’s ear simulator microphones in response to the pink noise stimulus. SPL measurements were recorded for one-third-octave bands with center frequencies ranging from 63 Hz to 16,000 Hz.

Ear simulator microphone SPLs were recorded for both open and occluded ear conditions. Three measurements were recorded for each occluded condition, with the metal isolation cap or HPDs under test removed and refitted between trials. The three occluded trials were averaged together for each ear before being subtracted from the open-ear levels to compute the IL. Each ear and frequency band were computed separately.

As discussed in the following sections, the occluded condition was different for the traditional and newly proposed SIL procedures. However, in both cases, the open-ear levels were measured with circumaural and earcanal flesh simulations in place. Figure 1 shows an example of the open-ear configuration for two types of ATFs used in this study.

2.2 Traditional self-insertion loss measurements

For traditional SIL measurements, all flesh simulations on the ATF are removed, and the ear simulators are blocked by solid metal isolation cups or plugs. Figure 2(a) shows a GRAS 45CB ATF with flesh simulations removed and replaced by solid metal caps covering the ear simulators. This configuration was used as the occluded ear condition for the traditional SIL measurements. Note that any flanking pathways that may be introduced by mounting the earcanal extension or circumaural flesh simulation on the ATF are likely mitigated by the solid metal cap in this setting.
2.3 Proposed self-insertion loss measurements

The goal in developing the proposed SIL measurement procedure is to ensure that the ATF is capable of measuring HPD IL up to the bone-conduction limits to attenuation. On human listeners, bone-conducted sound serves as a flanking path around an HPD. Even if an HPD could attenuate all air-conducted acoustic energy in the earcanal, the bone-conducted sound will still be heard during an occluded threshold measurement. Thus, the maximum attenuation measurable on a human listener is finite and limited due to bone-conduction effects. In our opinion, the ATF should be assembled as it will be for measuring HPD samples; in particular, any artificial flesh simulations should be in place and any heaters should be turned on.

Prior work has shown that the attenuation provided by deeply inserted foam earplugs, worn in combination with an earmuff, approaches the maximum attenuation possible for human listeners, due to the effects of bone-conducted sound [5]. Berger also found that with a deeply inserted plug, the choice of earmuff required to provide attenuation near the bone-conduction limits is not critical. When both were tested in combination with foam earplugs, lightweight earmuffs with small cup volumes yielded attenuation similar to large-volume earmuffs made of lead [6].

With this in mind, and given the goal of measuring insertion loss equal to or greater than the bone-conduction limits to attenuation, we propose measuring the SIL of a fully assembled ATF with deeply inserted foam earplugs in combination with an earmuff. This configuration serves as the occluded-ear measurement, to be paired with the open-ear measurement described in Section 2.1.

The key component is the deeply inserted, high-attenuation earplug. The choice of earmuff is less critical. In this study, the HPDs pictured in Fig. 2(b) were used. The foam earplugs were the 3M™ E-A-Rsoft™ Yellow Neons™ bullet-shaped polyurethane earplugs, which were paired with the 3M™ PELTOR™ Optime™ 101 Earmuffs H7A. Fig. 2(c) shows a GRAS 45CB ATF with these HPDs in place, as used for the occluded condition of the proposed SIL measurement. In principle, any bullet-shaped polyurethane or similar earplug (125 Hz real-ear attenuation \( \geq 35 \text{ dB} \)) and any moderate or higher...
attenuation earmuff (125 Hz real-ear attenuation $\geq 15$ dB) should be suitable.

3. Results

Table 1 lists the SIL limits standardized in ANSI/ASA S12.42-2010. For an ATF to meet the requirements of that standard, its SIL must meet or exceed these values when measured with the traditional procedure. As an additional quality check, we propose that the ATF should also meet the proposed SIL limits in Table 1, when measured using the procedure proposed in Section 2.3. These limits should be met by both ears of the ATF, with each ear measured individually. For reference, the human bone-conduction limits to attenuation that guided the development of the proposed SIL limits are also listed in Table 1. All of the values listed in Table 1 are also presented graphically in Fig. 3.

Figure 3 also shows the SIL measured on a GRAS 45CB ATF, using the traditional procedure with metal isolation caps. The measurements exceed the 60 dB criteria from 80 Hz to 12 500 Hz, also shown in Fig. 3 as the dashed red line. It is not practical to obtain similar measurements on an ISL-B ATF once it has been manufactured and shipped to a test laboratory, due to the assembly of the ear simulators. However, comparable measurements were made as part of the qualification process of the ATF when it was constructed at ISL. Data supplied by the manufacturer indicate that the traditionally-measured SIL exceeds 70 dB across the same frequency range [7].

Table 1: Self-insertion loss (SIL) limits to be met by acoustical test fixtures. Standard limits applicable to traditional SIL measurement method from ANSI/ASA S12.42-2010. Proposed values for new SIL measurement method discussed in the text. Standard limits to attenuation due to bone-conduction (BC) effects from ANSI/ASA S12.42-2010 included for reference.

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<td>BC Limit (head covered) (dB)</td>
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Figure 4 shows the results of the proposed SIL measurement procedure, as measured on two different samples of the GRAS 45CB ATF. Except for the right ear of ATF #2, both samples essentially meet the proposed SIL limits. Experience with this ATF at several acoustical laboratories has shown that the tightness of the set screws used to fasten the ear simulators in place can lead to a degradation in SIL performance. The right-ear results from ATF #2 might be improved by considering such an effect.

SIL measurements were also obtained on three samples of the ISL-B ATF using the proposed procedure. These results are shown in Fig. 5. Significant differences in SIL were noted between the two ears of ATF #2, highlighting the importance of testing both ears separately. The left ear of ATF #2 falls below the proposed limit curve at several frequencies. This ATF should be evaluated and repaired before being used for further HPD measurements. The other two ATF samples essentially meet the proposed SIL
Figure 3: SIL limits for the traditional and proposed measurement procedures. Also shown are the bone-conduction limits to attenuation as standardized in ANSI/ASA S12.42-2010 and SIL measurement results using the traditional procedure on a GRAS 45CB ATF.

Figure 4: SIL measurement results using the proposed procedure on two GRAS 45CB ATFs.
requirements. Their low-frequency SIL performance might be further improved with vibration isolation between the ATF and its measurement stand.

4. Discussion

In developing the proposed SIL procedure and limits, the goal of measuring insertion loss exceeding the bone-conduction limits to attenuation had to be balanced with the practical limitations of currently commercially available ATFs. The ATFs used in this study represent the current state-of-the-art in acoustical measurement technology. Several laboratories around the world currently use these or similar ATFs for HPD measurements according to the referenced standards.

The SIL measurement procedure and limits proposed in this paper were developed with the hope of increasing the reliability of HPD IL measurements taken according to ATF measurement standards. The authors are active participants in the development and revision of these standards, and they intend to propose these methods and requirements for inclusion in future standard revisions.

So that current ATFs are not unduly excluded, the SIL limits proposed here are less than the bone-conduction limits to attenuation at some frequencies. Hopefully the future of measurement technology brings commercially available ATFs capable of exceeding the bone-conduction attenuation limits. Until then, the procedure and limits proposed here are offered as an interim solution to ensuring the quality of insertion loss measurements obtained with the current generation of acoustical test fixtures.

5. Acknowledgments

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REFERENCES


