Calculation of laboratory spectrum uncertainty for various categories of hearing protectors

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ABSTRACT

Hearing protection devices (HPD) are commonly used to protect workers exposed to dangerous levels of noise, and their effective attenuation can now be routinely assessed using fit testing system, also known as Field Attenuation Estimation Systems (FAES). FAES typically rely on the use of the Noise Level Reduction Statistics (NRSA), a single number factoring in the attenuation obtained at the seven octave band frequencies from 125 to 8000 Hz, and accounting for the spectrum uncertainty component resulting from different slopes in the HPD attenuation across these frequencies. In the current study, this spectrum uncertainty has been computed from the NIOSH Hearing Protector Device Compendium (NIOSH 2004), a large database of typical laboratory attenuations, for a large number of HPDs (n=340). The spectral uncertainty has been found to range from 0.4 dB to 4.8 dB. The study also includes a detailed spectrum uncertainty budget for the various categories of earplugs (roll-down foam, premolded), semi-inserts and earmuffs. These values could be used as reference values in the upcoming ANSI S12.71 standard on FAES.

Keywords: Noise Control, Hearing Protection Devices, Fit-testing, Field Attenuation Estimation Systems, Spectral Uncertainty

I-INCE Classification of Subjects Number(s): 36, 36.1, 36.2, 36.3

1. INTRODUCTION

Noise-induced hearing loss (NIHL) is the most common occupational injury in Western countries and represents a substantial health burden both nationally and globally (1). Hearing loss has a substantial impact on the individual worker and on society as a whole in terms of health, economics, and quality of life (2). While NIHL is permanent and irreversible, it is also completely preventable, pending appropriate protection against noise exposure had been put in place.

While noise control at the source remains the objective for proper protection of workers against NIHL, hearing protection devices (HPD) are, for practical and economic reasons, often used as the first, if not the only, line of defense. For the purpose of labeling hearing protectors as to their comparative capability, the attenuation of HPDs is typically measured using the REAT procedure following ANSI/ASA S12.6 (3) or ISO 4869-1 (4) standards: the auditory thresholds are alternately measured for the unprotected (open) ear and for the protected (occluded) ear and the difference at every test frequency of the open and occluded auditory thresholds is averaged across a group of subjects to represent the nominal attenuation of the HPD under test. While the REAT test method is known to have several limitations, it is considered the “gold standard” for measuring an HPD's attenuation and all single number ratings like the single number rating (SNR) or the noise reduction rating (NRR) are computed from the attenuation data obtained from these laboratory attenuation measurements.

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1.1 HPD Fit-testing

In the field, however, the attenuations achieved by individual wearers of HPDs varies dramatically from these labeled laboratory values, for many reasons now well understood. For example, the NRR was designed to predict the amount of noise reduction that could be achieved by 98% of workers if they used the hearing protection as directed; however, research has shown that fewer than 5% of workers actually achieve the level of protection predicted by the NRR (5, 6).

To address the critical question of how much an individual user in the field is getting from his HPDs, field attenuation estimation systems (FAES), colloquially referred to as "fit-test" have been developed over the years. While fit-test technology has been available for research in many forms for over 40 years (7), the number and variety of commercially available FAES have been rapidly increasing since the early 2000s (8, 9), to the point that the OSHA-NHCA-NIOSH Alliance has identified individual fit-testing as an emerging trend and best practice (10). Because of the wide range of technologies used it was determined that a standard would be helpful to ensure precision and accuracy of FAES measurement outcomes. The development of such a standard is in process under the auspices of the Acoustical Society of America (ASA) and the American National Standards Institute (ANSI), designated ASA/BSR S12.71-201x. The Working Group S12/WG 11, Hearing Protector Attenuation and Performance, has prepared an initial draft of a standard and is continuing to work to finalize this for balloting and approval (11).

1.2 Personal Attenuation Rating

In its current draft format, ANSI S12.71 specifies minimum performance criteria for systems designed to estimate the real-ear attenuation provided by HPDs on individual users. The performance criteria are intended to ensure that FAES complying with the standard provide comparable test results to a reference laboratory procedure. Accuracy and precision are assessed by comparison of FAES data to those from the standard REAT procedure (ANSI, 2008) for the same fit of the device on an identical group of test subjects. This standard also specifies the procedures for the computation of the PAR, the personal attenuation rating. The PAR is an NRR-like number, but since it is based on the data from one wearer who is the actual user of the device, instead of a group of 10-20 subjects, the between-subject standard deviation correction that is included in the NRR computation is not needed. However, as with any single-number rating such as the NRR, the spectral variability must be accounted for. With the NRR this is accomplished using a constant 3-dB spectral safety factor, whereas the PAR accomplishes this with an explicit protection performance value that results from the variability in the computations using the 100 NIOSH noises. The PAR can be directly subtracted from A-weighted noise measurements instead of requiring the use of C weighted values as is recommended with application of the NRR. The computational details of the PAR are beyond the scope of this paper but can be found in (12) together with a comparison to other attenuation ratings and metrics. Ultimately, these calculations lead to the following equations:

$$\mathrm{PAR}_x = \mathrm{FAES_A} - \alpha \cdot u_{\mathrm{FAES_A}} \tag{1}$$

where

$$u_{\mathrm{FAES_A}} = \sqrt{s^2_{\mathrm{measurement}} + s^2_{\mathrm{fit}} + s^2_{\mathrm{spectrum}}} \tag{2}$$

with $\mathrm{FAES_A}$ the overall A-weighted attenuation of the HPD estimated by the fit-test system, α the coverage factor, and $u_{\mathrm{FAES_A}}$ the combined uncertainty defined as the square root of the sum of the measurement, fit and spectrum uncertainty components. The measurement uncertainty pertains to the intrinsic precision and accuracy of the FAES system in prediction the attenuation that would be measured using REAT for the same fit of the HPD under test. The fit variability pertains to the variability in the attenuation of the HPD from one fit to the next. The spectrum uncertainty is detailed hereafter.

1.3 Spectrum Uncertainty

As already mentioned, the spectrum uncertainty arises when a fit-test system provides a single number such as a PAR that is to be applied to A-weighted sound level measurements of noises with unknown spectral content. Depending on the actual noise spectral content, there can be a variation between the attenuation predicted using an octave-band calculation (usually on 7 octave-bands) applied to the actual octave-band noise data, versus that achieved with a PAR, which is analogous to the single number approach described in ANSI S12.68 (13). The spectrum uncertainty can be easily computed with computer–based fit test systems, by computing the difference between the incident A-weighted sound levels and the A-weighted sound levels effective when the HPD is worn, over all the noise of NIOSH 100 database of industrial noise spectra and reported as the third term in Eq. 2 to compute PAR from Eq.1. The difficulty however arises for FAES that do not report attenuation estimates on all 7 octave-bands. While it has been shown that good estimation of the overall A-weighted attenuation could be achieved with a reduced subset of octave-band attenuation values (14), fit-test system that report attenuation values at less than 2 octave-bands are fundamentally not capable of computing the spectrum uncertainty as per the prescribed ANSI S12.68 derived approach.

The goal of this paper is to provide an offline estimate of the spectrum uncertainty component for various types of HPD from their laboratory attenuation data, so that conservative values could be tabulated for inclusion with the calculation of PAR for FAES that do not report at least 2-octave band attenuation values.

The method used for the offline computation is presented in section 2, while section 3 will detail the values obtained on 4 different types of HPD. Finally a recommendation on which value to include in the upcoming ANSI S12.71 standard will be made in section 4.

2. METHOD

2.1 NIOSH HPD Compendium

The NIOSH Hearing Protector Device Compendium is a comprehensive searchable database of hearing protection devices available as a web tool on the National Institute for Occupational Safety and Health website (15). It was originally created to help workers and safety professionals select the most appropriate product for their unique environment. The tool identifies hearing protector devices by type, manufacturer, and noise exposure level. It also explains essential product features, including desired noise reduction ratings, mean attenuations, standard deviations of attenuations, protector construction and materials, and other features that can aid the selection of protectors for specific situations. In the present study, an export of the 2004 version of this database was used. Many companies that were listed in the 2004 compendium have now merged with other companies or have ceased to manufacturer or sell hearing protectors, hence the 2004 version of the database is larger than the current NIOSH HPD Compendium. The protectors in the NIOSH database file were de-identified to remove manufacturer and product names and retained the octave-band attenuation values for 245 earmuffs, 66 foam earplugs, 42 premolded earplugs and 33 semi-aural insert protectors. While the total number of records from the database was actually 386, due to tests reported for multiple position there were 340 distinct products. For this reason, the results will be presented for all the four types of HPD and then for all HPDs. The results for the "earmuffs" type includes all variants in position for wearing, while the "all" type only include the standard position for wearing for each earmuff HPD.

2.2 Spectrum Uncertainty Calculation

As mentioned is Section 1.1, the spectrum uncertainty is obtained by computing the difference between the incident A-weighted sound levels and the effective A-weighted sound levels when the HPD is worn, over all the noise of NIOSH 100 database of industrial noise spectra. The NIOSH 100 noise database are given in ANSI S12.68 Annex A and the computation of the spectrum uncertainty can computed according to Eq. 3, and is similar to the uncertainty defined in ANSI/ASA S12.68:

$$s_{\text{spectrum}}(n) = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}\left(\Delta L_{\text{A, FAES}}(n) - \overline{\Delta L_{\text{A, FAES}}}\right)^2} \tag{3}$$

where $\Delta L_{\text{A, FAES}}(n)$ is the overall difference between the incident A-weighted sound levels and the A-weighted sound levels effective when the HPD, index *n*, is worn, using the octave-band FAES attenuation, and $\overline{\Delta L_{\mathrm{A,\,FAES}}}$ is averaged across the NIOSH 100 noises. For each HPD, index n, within an HPD type group, this spectrum uncertainty is computed, using Matlab (Mathworks, Natick, MA, USA) scientific programming software. Descriptive statistics can then be computed on the different values of spectrum uncertainty computed for the various types of HPDs.

3. RESULTS

3.1 HPD Octave-Band Attenuation

The mean octave band attenuation values are presented in Table 1 below for the four different HPD types and for the all 340 HPDs. As it can be seen, these attenuation values are high for some HPD types, like the foam plugs, as these attenuation values are directly obtained from the labeled attenuation values provided by the HPD manufacturers to the NIOSH compendium database.

Table 1 – Mean octave band attenuation of the different HPD types.

Octave-Band Center Frequency (Hz)	125	250	500	1000	2000	4000	8000
All (N=340)	21.3	24.6	30.2	34.4	34.6	38.5	41.9
Semi-Inserts (N=33)	26.2	26.0	26.3	27.6	33.9	38.7	40.1
Premolded (N=42)	28.6	29.1	29.9	31.1	34.7	38.3	52.8
Foam (N=66)	31.4	34.3	37.2	36.7	36.8	42.9	44.8
Earmuffs (N=245)	16.6	21.6	29.7	35.8	35.6	37.3	39.6

3.2 Spectrum Uncertainty

Table 2 presents the distribution parameter estimates and the number of observations, *N*, for the spectrum uncertainty data. The *min*, *max*, *mean*, *median* and *std* variables represent, in dB, respectively the minimum value, maximum value, sample mean, sample media (50^{th} percentile) and sample standard deviation for the spectrum uncertainty of the different HPD types.

Table 2 – Distribution parameter estimates and the number of observations for the spectrum uncertainty data of the different HPD types.

HPD Type	All	Semi-Inserts	Premolded	Foam	Earmuffs
N	340	33	42	66	245
min	0.40	0.68	1.19	0.65	0.85
max	4.82	3.16	3.37	4.51	4.82
mean	2.66	2.26	1.82	1.45	3.18
median	2.70	2.25	1.74	1.32	3.35
std deviation	1.05	0.61	0.43	0.68	0.87

3.3 Spectrum Uncertainty Cumulative Distributions

Fig. 1 represent the empirical cumulative distribution of the spectrum uncertainty for each of the four types of HPD, and for the whole database of 340 different HPD models. These cumulative distributions are plotted on a range of 0 to 5 dB, as this later value represents the highest integer value of spectrum uncertainty across all the HPDs of the NIOSH Hearing Protector Device Compendium Database.

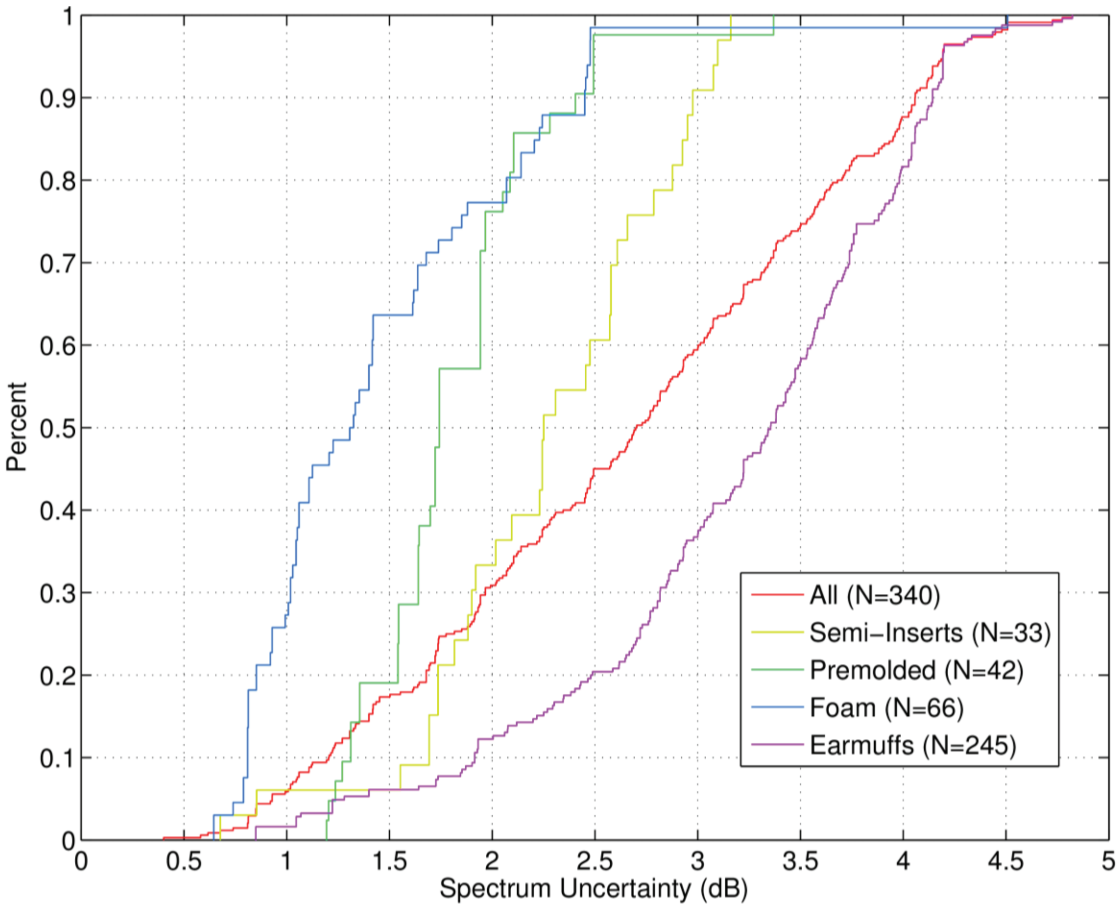

Figure 1 – Empirical cumulative distribution function of the spectrum uncertainty computed for each of the four types of HPDs

3.4 PAR vs Spectrum Uncertainty

To better understand what drives the value of the spectrum uncertainty, a scatterplot of the computed spectrum uncertainty vs. the overall attenuation of the HPD is presented in Fig. 2 for the four types of HPDs. This overall attenuation is computed using the PAR calculation method, i.e. it represents the difference between the incident A-weighted sound levels and the effective A-weighted sound levels when the HPD is worn over all the noise of NIOSH 100 database of industrial noise spectra.

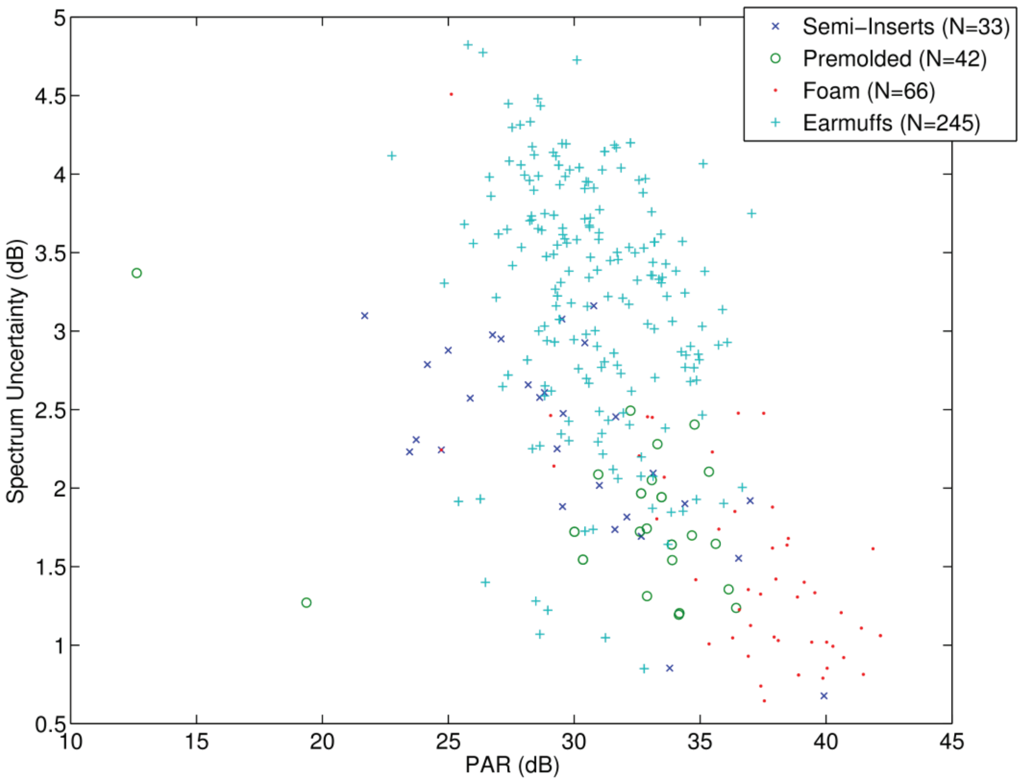

Figure 2 – Scatterplot of spectrum uncertainty value as a function of overall PAR attenuation value

4. DISCUSSION

4.1 Spectrum Uncertainty Cumulative Distributions

The empirical cumulative distribution function of the spectrum variability in Figure 1 clearly rises quickly. The spectrum uncertainty distributions for the premolded and foam earplugs exceed 2.5 dB only for one or two samples, representing a very minor percentage of the premolded and foam earplugs. As such the maximum uncertainty of 4.5 dB, presented in Table 1, for foam plug really only represent one HPD. For semi-inserts, the spectrum uncertainty empirical cumulative distribution rises progressively, reaching 3.4 dB. Finally the earmuffs have the slowest rising cumulative distribution, ranging over a span of 0.8 to 4.8 dB.

4.2 PAR vs Spectrum Uncertainty

Without sophisticated statistical analysis, a rough trend could be seen from Fig. 2, as the HPD showing the highest attenuation (reported in terms of overall PAR on the x-axis) do also exhibit the lowest spectrum uncertainty. This is very visible for foam plugs (red dots) that reach the highest attenuation while having the lowest spectrum uncertainty and can be explained by the fact that such HPD, when deeply fitted inside a subject's earcanal provide a very high and almost "flat" attenuation that does not change across frequencies. As such, the change in the spectrum of the noise is of very little influence on the overall A-weighted attenuation that this HPD will provide.

This observation is of importance, as the calculations of the spectrum uncertainty were conducted on the laboratory attenuation data provided by the manufacturers, hence on HPDs that may be much better fitted than in real-life situations. The trend as seen in Fig. 2 suggests that protectors with less attenuation potentially may exhibit higher spectrum uncertainty, it is important to not underestimate the upper limit of spectrum uncertainty. For these reasons, the authors felt that the maximum value of the spectrum uncertainty found in these off-line calculation should be used as a safe estimate, rather than a lower percentile value.

5. CONCLUSIONS

It has been found that the spectrum uncertainty component for 340 HPDs representative of current product on the market is ranging from 0.4 dB to 4.8 dB. This upper value could also be split across HPD type and would be respectively of 3.2 dB, 3.4 dB, 4.5 dB for semi-inserts, premolded, foam earplugs and 4.8 dB for earmuffs. Nevertheless, as the spectrum uncertainty calculations were conducted here on the laboratory attenuation data reported by the HPDs manufacturers, it is felts that 4.8 dB should be considered as a safe estimate of the spectrum uncertainty to be used for the computation of the Personal Attenuation Rating for a fit-test system that would not support complex octave-band calculation. This value could be used as reference values in the upcoming ANSI S12.71 standard on FAES.

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