IS IT NECESSARY TO MEASURE HEARING PROTECTORS ATTENUATION AT 4 AND 8 KHZ?

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ABSTRACT

A Microphone In Real Ear (MIRE) technique specifically designed to measure Hearing Protection Device (HPD) attenuation in the field has been recently made available on a large scale. Some detailed studies of such measurement system, often referred to as "Field-MIRE" or "F-MIRE" systems, have also made clear that the measurement attenuation for the high frequencies (typically in the 2, 4 and 8 kHz Octave Bands) could become surprisingly variable over time, for a same fit of an HPD on a human subject. After thorough investigation, and because the measurement system itself had been demonstrated to be reliable, the reason for that large variability appears to be basically related to the difficulty of objectively measuring -with a somewhat modified probe microphone- a Sound Pressure Level (SPL) in a small occluded cavity. Indeed, for these high frequencies, the sound wavelength becomes short compared to the length of the microphone probe tube used and any slight dimensional change of the occluded ear-canal can dramatically change the reading of the SPL measurement. Even if such variability in the measured HPD attenuation is not caused by the measurement system itself (that simply "revealed" this change because of its high sensitivity) but really associated with the physical system under measurement (an occluded ear-canal that is constantly slightly changing in dimension, because of jaws movements and skin tissue capillary blood flow), it is still of interest to understand how this variability in high-frequency is affecting the overall reported attenuation value. In a first statistical analysis, the sensitivity of an overall attenuation value (like the Noise Reduction Rating (NRR) in ANSI standards or Single Noise Rating (SNR) in ISO standards) to the high-frequency attenuation has been studied by computing the NRR and SNR with and without these octave-bands for all HPD available in the "NIOSH HPD Compendium". A second statistical analysis has looked into the sensitivity of the Noise Reduction Level Statistics (NRS), a new attenuation rating system recently promoted in ANSI S12.68 that takes into account the typical noise spectrum found in industrial plants. Finally, the effects of the variability of the F-MIRE measured attenuation in high-frequency on the measurement uncertainty has been studied and found to be negligible in practise, while the attenuation at 4 and 8 kHz had been found to be usually not necessary to measure for proper HPD overall rating.

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1. INTRODUCTION

Existing standards for the measurement of Hearing Protection Devices (HPD) attenuation are relying the attenuation measurement using the Real Ear Attenuation at Threshold (REAT) and are performed on third-octave bands centred on central frequencies ranking from 63 Hz or 125 Hz to 8000 Hz. The measurement of HPD attenuation using the REAT method is covered by several standards. The ANSI S3.19 [1], first adopted in 1974, is relying on 10 subjects fitted by the laboratory technician and tested three times each for a given HPD. The more recent ANSI S12.6 [2], is relying on two trials on either on 15 or 20 subjects (for earmuffs and earplugs respectively), whose HPD have been fitted by the subject, either trained and supervised ("Method A") or inexperienced and autonomous ("Method B"). International Standard ISO 4869-1 [3] corresponds to Method A of ANSI S12.6, while ISO 4869-5 [4] corresponds to Method B of ANSI S12.6. Finally, the Australian AS/NZ 1270 relies on two trials on 16 to 20 subjects (for earmuffs and earplugs respectively) that fitted the HPD by themselves using only the written manufacturer's instructions. Single Numbers Measures (SNM) [5] are usually expressing overall attenuation on these measured octave bands with, 63 Hz (for ISO standards) or 125 Hz to 8000 Hz.

In practise, however, the typical attenuation of an HPD is higher for the high frequencies than for the low frequencies, hence the overall attenuation is usually driven by low or mid-frequencies and some authors were already quite successfully able to link attenuation measured at low frequencies to predict the overall HPD attenuation [1][2][3][4]).
Besides that, acoustical measurements become more delicate as the acoustical wavelength diminishes: high frequency attenuation measurement are indeed very sensible to slight physical displacements such as the subject's head placement in the sound room (in the case of REAT attenuation measurement technique) or the microphones positioning in the vicinity of the hearing protector (in the case of the Microphone in Real Ear (MIRE) technique [5][6]).

It is therefore reasonable to ask if the measurement of the attenuation for high frequencies is useful for the assessment of the overall attenuation of an HPD, and to specifically examine if the 4 and 8 kHz octave-band attenuation data are creating more disturbances (because they are so difficult to measure, hence so variable) than they can actually contribute to the accuracy and precision of the overall attenuation value. The title of this paper is on purpose very similar to a Berger and Rowland article [7] that concluded that there is little value in measuring real-ear attenuation in a diffuse sound field at the frequencies of 3.15 and 6.3 kHz for applications in which hearing protector attenuation data are normally utilized. The present article will use the same computational approach, by comparing the overall values that would be obtained with all frequency bands combined to the attenuation that would be obtained with a more restricted set of octave band data. Such difference, dubbed "limited bandwidth" rating error (LBE) for the present article, will be computed with various parameters such as the frequency range used, the type of single number used and the HPD model used.

The article with first present, in section 2, the observed variability of F-MIRE high frequency attenuation over time, that motivated the authors to investigate if such variability was actually harmfully for the overall precision and accuracy of the F-MIRE technique. Section 3 will present the various parameters that will be examined for the computation of the LBE, together with the computational details. Section 4 will present the results, essentially as error distribution graphs, while section 5 will present the benefits of using a limited bandwidth single number in the case of the F-MIRE method.

2. HIGH FREQUENCY F-MIRE VARIABILITY: THE TRIGGER

A sequence of 90 consecutive F-MIRE measurements has been conducted in September 2006 at AEARO E-A-Rcal laboratories (Indianapolis, IN) using the Sonomax's SonoPass™ (Montreal, Canada) measurement system on an E-A-R UltraFit™ premolded earplug fitted on one ear of a single subject [8].

The figure 1 below represents the -uncorrected and uncompensated- raw Noise Reduction (NR) data for each of the 7 octave bands measured (from 125 Hz to 8 kHz) with a measurement cycle time of approximatively 10 seconds. One can notice that the attenuation is fluctuating over time, despite the fact that the seated subject was asked to remain quiet. It is also noticeable that the magnitude of these fluctuations is not necessary related to the level of Noise Reduction: for example, the NR measured for 1 kHz is close to 0 dB but shows more variability than the level for 2 kHz that is around 7 dB. Rather, it seems that the magnitude of the fluctuation of the measured Noise Reduction appears to be larger for high frequencies than for low frequencies: the largest fluctuation is observed for 8 kHz (with more than 6 dB excursions) and for 4 kHz (with almost 4 dB excursions).

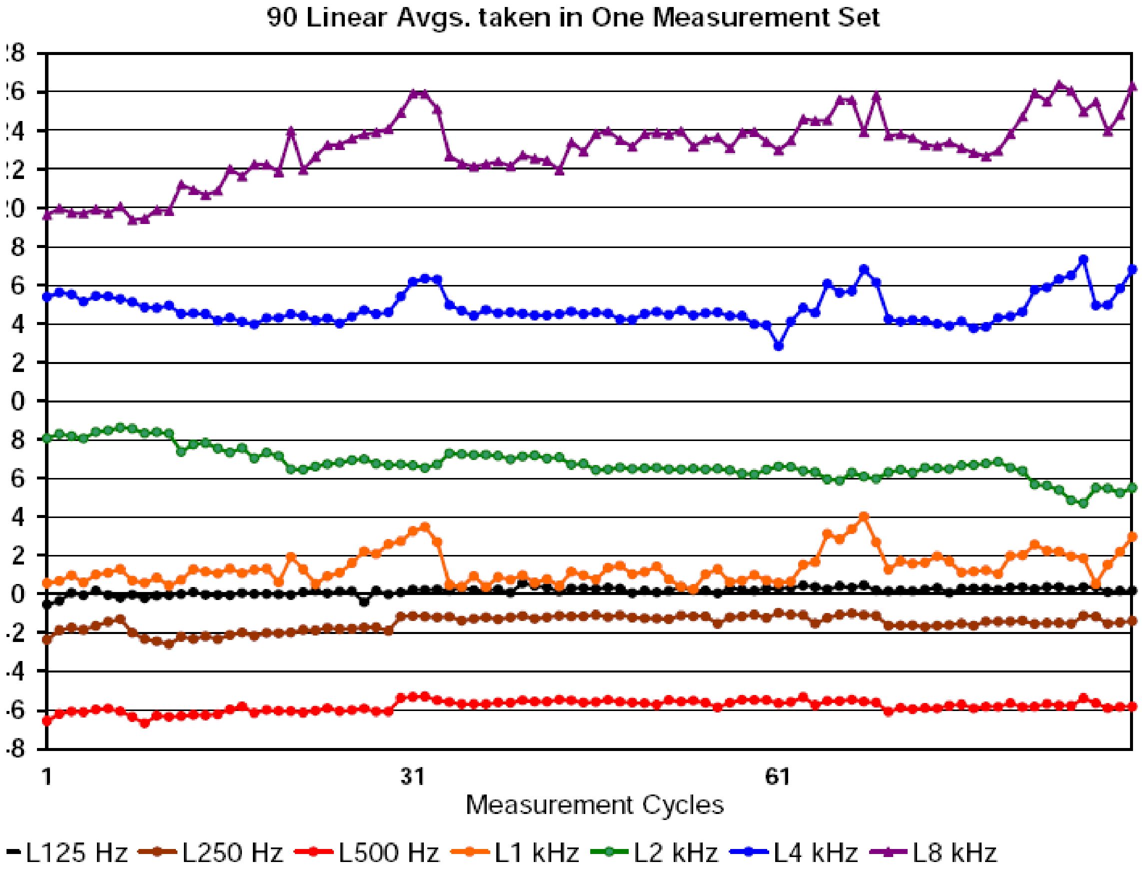

Figure 1: Octave-band Noise Reduction data (in unreferenced dB) obtained from 90 consecutive F-MIRE measurements (approx. 10 sec. each) on an E-A-R Ultrafit™ premolded earplug in one ear of a seated and quiet human test subject (from [8]).

Few other observations can be made, such as the NR peaking around cycles #31 and #65 in Fig. 1 above or such as a downward drift of the NR at 2 kHz. Such "anomalies" have been since re-observed with the same F-MIRE microphones but on a different data acquisition and analysis system [9][10], hence are not necessarily aberrant results (the F-MIRE measurement system did simply "revealed" this variability because of its high sensitivity) and would rather require future explanations (one could argue that the occluded ear-canal is constantly slightly changing in dimension, because of jaws movements and skin tissue capillary blood flow). Nevertheless, it is legitimate to investigate if such highly variable data at high-frequency is not creating more disturbances than beneficial contribution to the accuracy and precision of the overall attenuation value of the HPD under test.

3. LIMITED BANDWIDTH RATING ERROR (LBE) CALCULATION

This section will detail the computational details of the LBE for the various frequency range, type of single number used and HPD model used.

3.1. Frequency Range

The LBE will computed by comparing the Single Number Measure (SNM) obtained using all the octave-band attenuation data (as per the pertaining standards) to SNM obtained using a limited set of octave bands frequencies attenuation data. The high-frequencies octave band data that will be discarded from the computation can be either the 8 kHz band or the 4 and the 8 kHz. The SNM will hence be computed on 7 octave bands data from 125 to 8000 Hz (index i =1 to 7), 6 octave bands data from 125 to 4000 Hz (i =1 to 6) or only 5 octave bands from 125 to 2000 Hz (i =1 to 5).

3.2. Single Number Value Type

The LBE will be computed on the various frequency ranges mentioned above, using several existing SNM: NRR [11], SNR [12], SLC_{80} [13] and the lately proposed Noise Reduction Level Statistics (NRSA) [14]. Moreover, since these values are expressed for a group statistic, at a percentile value, they all include at one time or another, the use of the standard-deviation of the REAT attenuation values obtained on a subject test panel. Such standard deviation is subtracted from the group mean attenuation, in order to express a percentile value (assuming a normal distribution of the group attenuation values) that a SNM is. Typically, a SNM is expressed at a protection performance x , as defined in Table 1: the NRR is expressed at a protection performance of 98% (α =2), the SNR is often expressed at a protection performance of 84% (α =1), and SLC is expressed at protection performance factor of 84%, that is rounded to 80% (α =1). Since the proposed F-MIRE attenuation measurement is an individual measurement, no group standard-deviation value can be used as such (even if some intra-subject fit variability can be used in the Personal Attenuation Rating produced by such F-MIRE measurement; see Voix [15] for further details): the proposed analysis will then also be performed on the Single Number Values obtained at the 50th percentile (a protection performance factor of 50% corresponds to a coverage factor α=0 , hence is only using the average attenuation data for the HPD). Such calculation at the 50th percentile will also be presented in the calculation section below.

Table 1: Values of α for various protection performances (from [12]):

Protection Performance (in %)	Value of α
75	0.67
80	0.84
84	1.00
85	1.04
90	1.28
95	1.64
98	2

a) Noise Reduction Rating (NRR)

The NRR is computed according to the Environmental Protection Agency requirements [11], by subtracting a two-standard deviation correction from the mean REAT attenuation values in order to estimate the "minimum noise reduction theoretically achieved by 98% of the laboratory subjects". If attenuation data at 3.1 and 6.2 kHz is omitted (in accordance with what has been suggested by other authors [7]), the NRR could be expressed in the compact form below:

$$NRR_{98} = 10 \cdot \log_{10}\left(\sum_{i=1}^{7} 10^{\frac{100+C^i}{10}}\right) - 10 \cdot \log_{10}\left(\sum_{i=1}^{7} 10^{\frac{100+A^i-REAT^i+2\cdot\sigma^i_{REAT}}{10}}\right) - 3 \qquad (1)$$

where A^i and C^i are respectively the A-weighting and C-weighting octave band values given in the following table:

Table 2: Octave band weighting A^i and C^i (from [16]).

Octave Band Frequency (Hz)	125	250	500	1000	2000	4000	8000
i	1	2	3	4	5	6	7
C^i weighting (dB)	-0.2	0	0	0	-0.2	-0.8	-3
A^i weighting (dB)	-16.1	-8.6	-3.2	0	1.2	1.0	-1.1

Moreover, since the computation of the NRR is only used in a differential way (comparing NRR on the 7 octave-bands to the NRR on a more limited frequency range of 5 or 6 octave-bands), a simplified expression can be used:

$$NRR_x^I = 10 \cdot \log_{10}\left(\sum_{i=1}^{I} 10^{\frac{100+C^i}{10}}\right) - 10 \cdot \log_{10}\left(\sum_{i=1}^{I} 10^{\frac{100+A^i-REAT^i+\alpha\cdot\sigma^i_{REAT}}{10}}\right) \qquad (2)$$

where I is the maximum index of the octave-band frequency considered (I=7 for the 125-8000 Hz range, I=6 for the 125-4000 Hz range and I=5 for the 125-2000 Hz range) and where x is protection performance factor (typically x=98% for the NRR, x=84% for the SRR and x=80% for the SLC and NRS_A).

b) Single Number Rating (SNR)

The SNR is computed, per the ISO 4869-2 [12] as:

$$SNR_x = 100 - 10 \cdot \log_{10}\left(\sum_{i=1}^{7} 10^{\frac{L'_A - APV_x^i}{10}}\right) \tag{3}$$

where APV^i is the Assumed Protection Value.
Eq. 4 can be rewritten in a very similar way to Eq. 2, by realizing that the left term is simply the summation of octave-band sound pressure levels that have an overall value of 100 dBC. Hence, after a few transforms, it is also possible to express the SNR, in a very similar way to the previous $NRRx^I$ as:

$$SNR_x^I = 10 \cdot \log_{10}\left(\sum_{i=1}^{I} 10^{\frac{100+C^i}{10}}\right) - 10 \cdot \log_{10}\left(\sum_{i=1}^{I} 10^{\frac{100+A^i-REAT^i+\alpha\cdot\sigma_{REAT}^i}{10}}\right) \tag{4}$$

The factor α is a function of the protection performance x that is targeted. For example, for a protection performance of 98% (similar to Eq. 2), the value of α is 2.

c) Noise Reduction Level Statistics (NRS)

A substantial divergence in the ANSI S12.68-2007 [14] standard from prior publications and other standards ([17][18]) is that the NRS_A is a so-called "A – A'" rating: it predicts, by simple subtraction from the A-weighted ambient noise levels, the effective A-weighted levels $Lp'A$ when an HPD is worn. A – A' ratings, which by their very nature are straightforward, easier to use and less prone to computational errors, are of sufficient precision for most applications considering the many sources of variability inherent in predicting protection [19].

Its calculation begins by computing the A-weighted noise level reduction for each subject p for which attenuation data are available in each noise n of the NIOSH 100 database of industrial noise spectra (rather than only 8 spectra, as in the previous section):

$$\Delta L_{A_{pn}} = 10 \cdot \log_{10}\left(\sum_{i=1}^{7} 10^{\frac{L'_n+A^i}{10}}\right) - 10 \cdot \log_{10}\left(\sum_{i=1}^{7} 10^{\frac{L'_n+A^i-REAT_p^i}{10}}\right) \tag{5}$$

where $L^i n$ is the sound pressure level in decibels for the octave centred on i for the n th noise in an industrial noises database; $REAT^i p$ is the attenuation in decibels measured for the hearing protector on the p th subject at octave-band center frequency i, averaged across several trials (usually 2, as in the ANSI S12.6 [18]).

The NRS_A is defined as:

$$NRS_{Ax} = m - \alpha \cdot \sqrt{s_{subject}^2 + s_{spectrum}^2} \tag{6}$$

where m is the average attenuation across subjects across spectrum, obtained as:

$$m = \frac{1}{P \cdot N} \sum_{n=1}^{N} \sum_{p=1}^{P} \Delta L_{A_{pn}} \tag{7}$$

and the standard deviations $s_{subject}$ and $s_{spectrum}$ are respectively -classically- defined by:

$$s_{subject} = \sqrt{\frac{1}{P-1}\sum_{p=1}^{P}(m_p - m)^2} \tag{8}$$

and

$$s_{spectrum} = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}(m_n - m)^2} \tag{9}$$

3.3. HPD Type

The various LBE calculation scenarios presented previously, in order to be valid, should be applied to the largest HPD attenuation dataset possible. As mentioned on their website (*http://www.cdc.gov/niosh/topics/noise/hpcomp.html*), in 2000, NIOSH researchers initiated a new effort to collect data published by manufacturers of hearing protectors sold in the United States. The new data was sought to augment or replace the data last collected by NIOSH for the 1994 Hearing Protector Compendium [20]. The data included the mean attenuations and standard deviations of the attenuations provided by the manufacturers on labelling required by the U.S. Environmental Protection Agency. The compendium database, as received from the NIOSH in June 2007, contains 148 intra-aural HPD (earplugs) and 244 circum or supra-aural HPD (earmuffs, ear-caps, headbands, etc.) that has been used for this study.

4. LBE CALCULATION RESULTS

4.1.NRR analysis for earmuffs

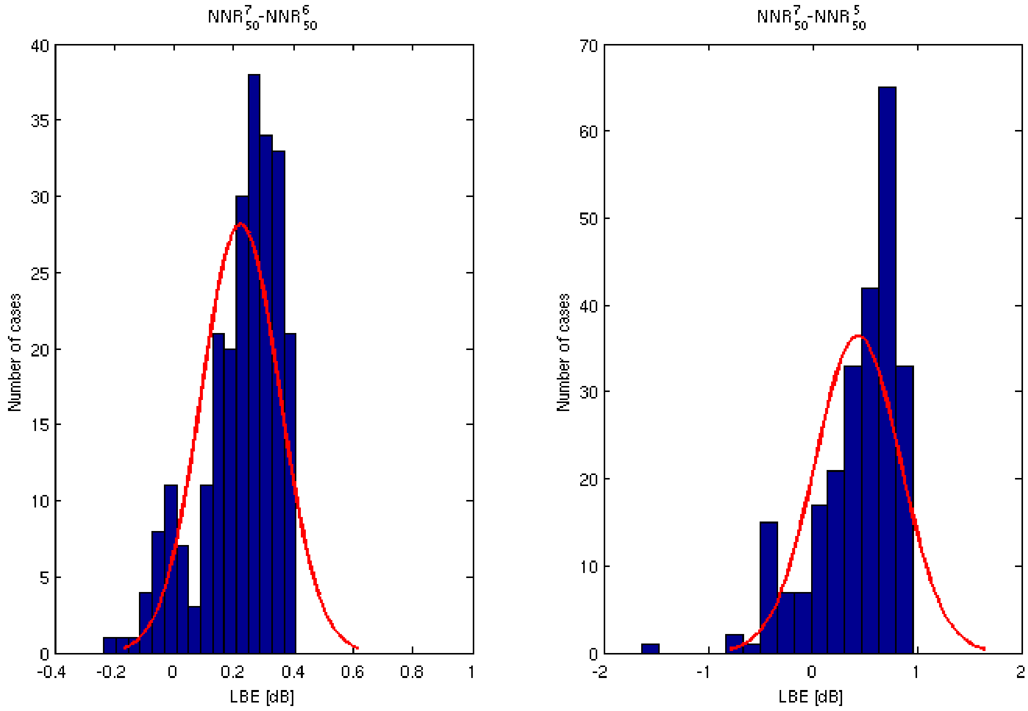

Figure 2: Histogram with superimposed fitted normal density of the LBE for 244 earmuffs, using the NNR_{50}^{7}-NNR_{50}^{6} (left) and the NNR_{50}^{7}-NNR_{50}^{5} (right).

As illustrated on Fig.2 above , all the 244 earmuffs models have an LBE ranking from -0.43 to +0.41 dB for NNR_{50}^{7}-NNR_{50}^{6} and from -0.79 to +0.94 at the exception of the "Peltor MT1H79B-

01327 Surround" (with -1.63 dB) for the $NNR50^{7}$-$NNR50^{5}$. None of the distributions can be considered as "normal", but the average and standard deviation are respectively 0.22 and 0.13 dB for $NNR50^{7}$-$NNR50^{6}$ and 0.43 and 0.41 dB for the $NNR50^{7}$-$NNR50^{5}$.

4.2.NRR analysis for earplugs

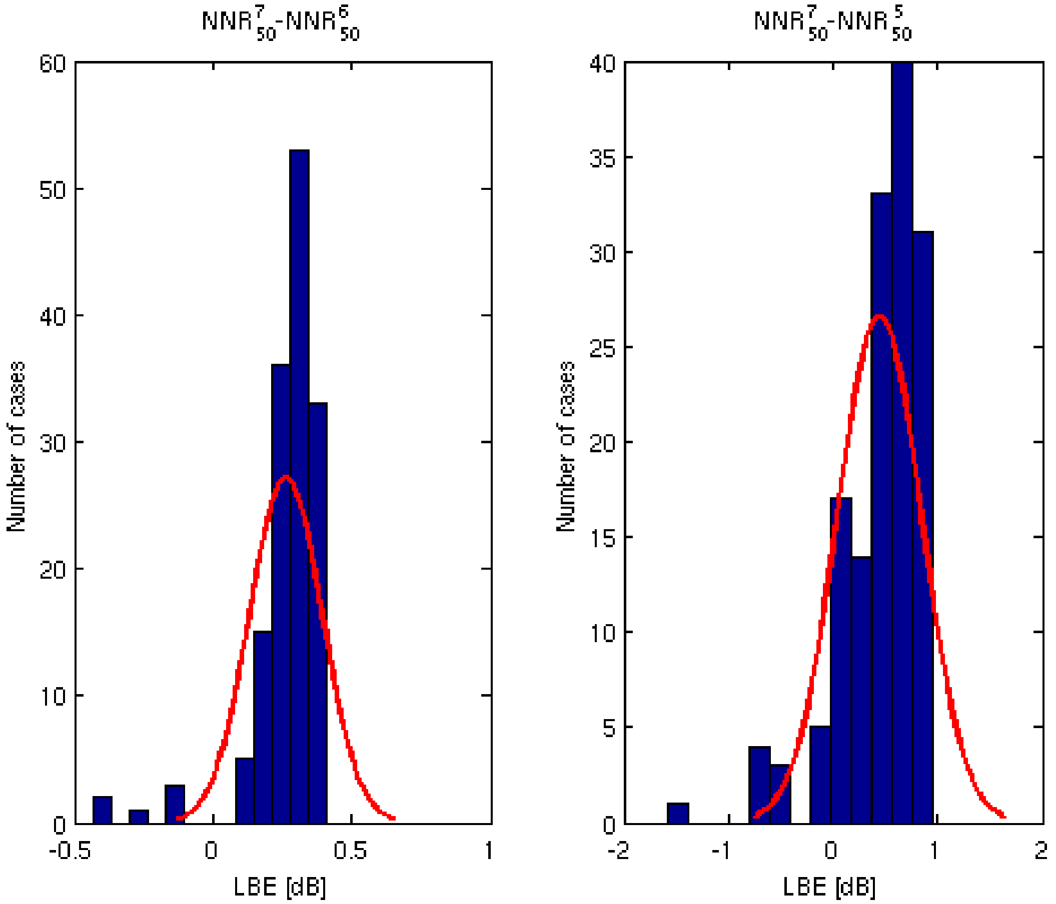

***Figure 3**: Histogram with superimposed fitted normal density of the LBE for 148 earplugs, using the $NNR50^{7}$-$NNR50^{6}$ (left) and the $NNR50^{7}$-$NNR50^{5}$ (right).*

As illustrated in Fig. 3 above, all the 148 earplugs models have an LBE ranking from -0.43 to +0.41 dB for $NNR50^{7}$-$NNR50^{6}$ and from -0.75 to +0.94 (at the exception of the "Precision Loboratorie ER-15" with -1.58 dB) for $NNR50^{7}$-$NNR50^{5}$. None of the distributions can be considered as "normal", but the average and standard deviation are respectively 0.26 and 0.13 dB for $NNR50^{7}$-$NNR50^{6}$ and 0.44 and 0.40 dB for the $NNR50^{7}$-$NNR50^{5}$.

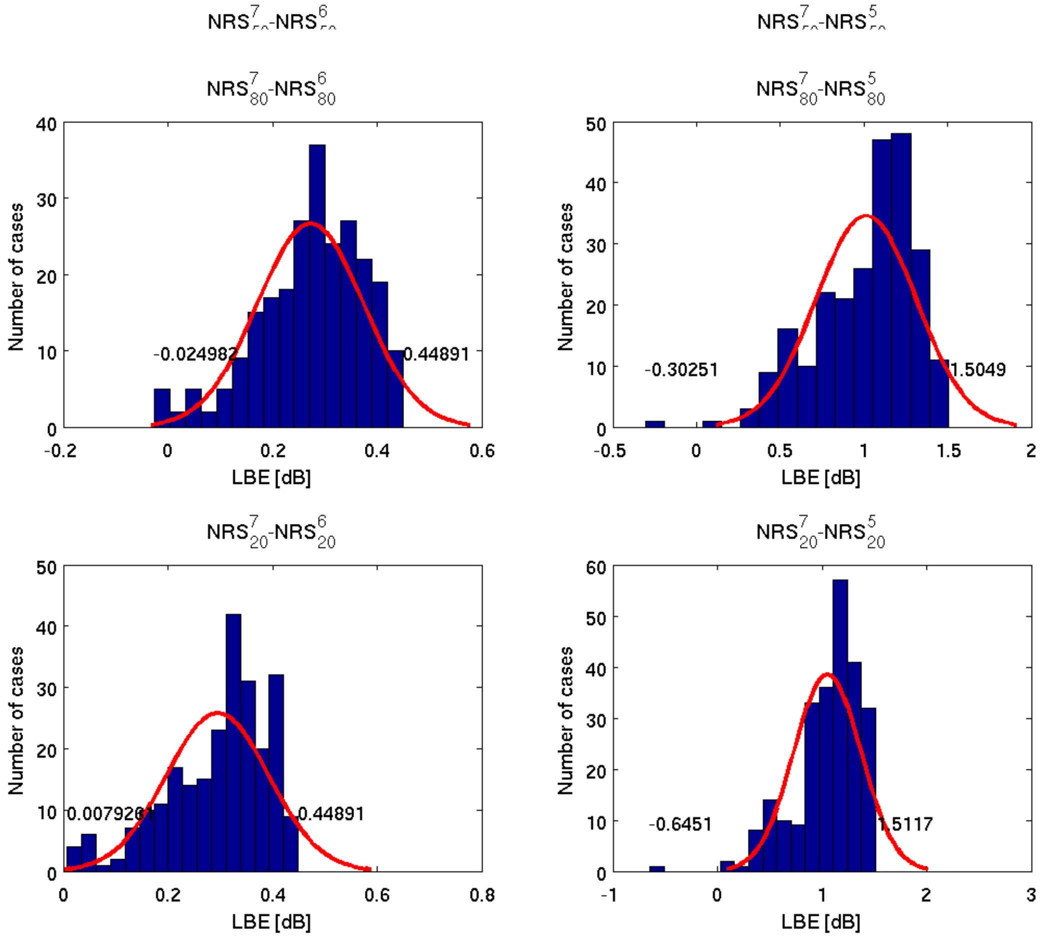

Figure 5: Histogram with superimposed fitted normal density of the LBE for 244 earmuffs, using the $NRS80^{7}$-$NRS80^{6}$ (upper left), the $NRS80^{7}$-$NRS80^{5}$ (upper right), the$NRS20^{7}$-$NRS20^{6}$ (lower left) and the $NRS20^{7}$-$NRS20^{5}$ (lower right).

NRS Analysis for Earmuffs

As illustrated in Fig. 5 above all the 244 earmuffs earplugs models have an LBE ranking from -0.02 to +0.45 dB for $NRS80^{7}$-$NRS80^{6}$, from -0.30 to +1.50 for $NRS80^{7}$-$NRS80^{5}$, from 0.07 to 0.45 dB for $NRS20^{7}$-$NRS20^{6}$ and from -0.64 to +1.51 for $NRS20^{7}$-$NRS20^{5}$.

4.3. NRS Analysis for Earplugs

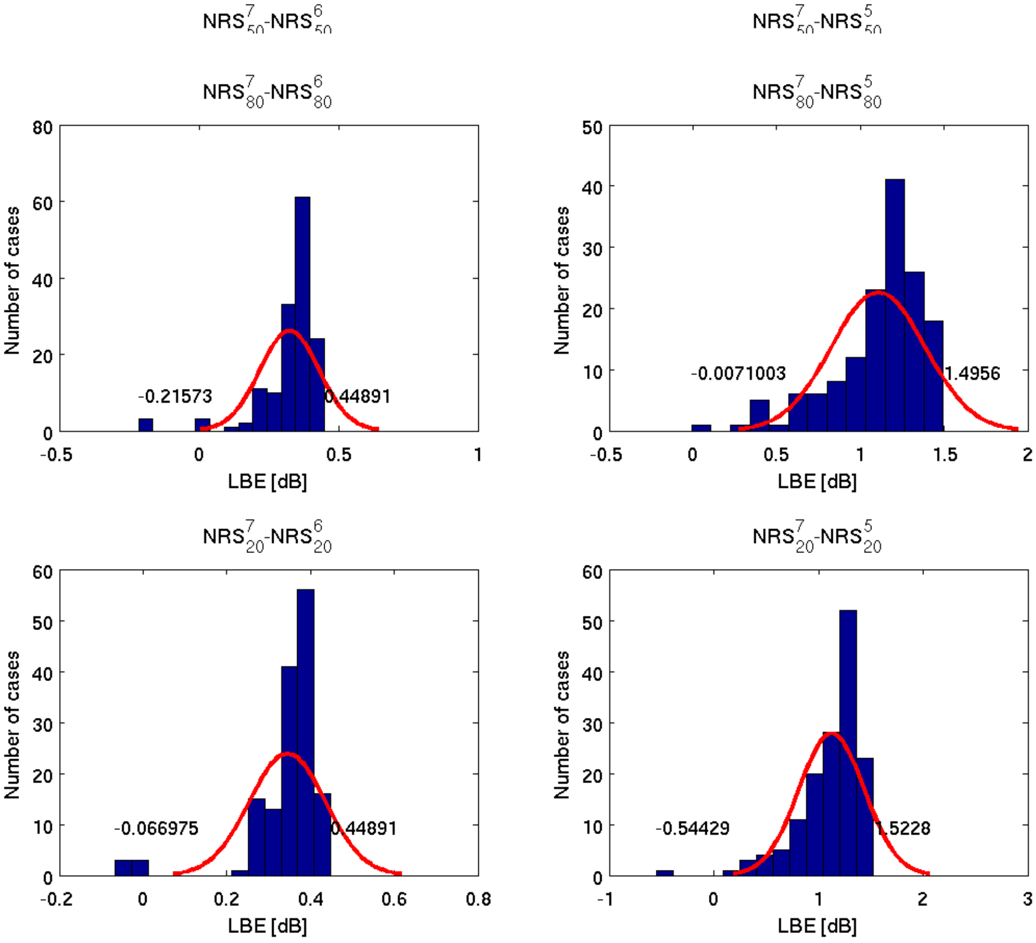

Figure 6**: Histogram with superimposed fitted normal density of the LBE for 148 earplugs, using the* $NRS80^{7}$*-*$NRS80^{6}$ ***(upper left), the $NRS80^{7}$*-*$NRS80^{5}$ ***(upper right), the*** $NRS20^{7}$*-*$NRS20^{6}$ ***(lower left) and the*** $NRS20^{7}$*-*$NRS20^{5}$ ***(lower right).***

As illustrated in Fig. 6 above all the 148 earplugs models have an LBE ranking from -0.14 to +0.44 dB for $NRS50^{7}$-$NRS50^{6}$ and from -0.27 to +1.50 for $NRS50^{7}$-$NRS50^{5}$.
None of the distributions can be considered as "normal", but the average and standard deviation are respectively 0.33 and 0.10 dB for $NRS50^{7}$-$NRS50^{6}$ and 1.12 and 0.30 dB for the $NRS50^{7}$-$NRS50^{5}$.

As illustrated in Fig. 7 above all the 148 earplugs models have an LBE ranking from -0.22 to +0.45 dB for $NRS80^{7}$-$NRS80^{6}$, from -0.01 to +1.50 for $NRS80^{7}$-$NRS80^{5}$, from -0.07 to +0.45 dB for $NRS20^{7}$-$NRS20^{6}$ and from -0.54 to +1.52 for $NRS20^{7}$-$NRS20^{5}$.

5. BENEFITS OF "LIMITED BANDWITH" FOR THE F-MIRE TECHNIQUE

Fig. 8 below reproduces (from [21]) the comparison between REAT and F-MIRE of the overall attenuation values of the twenty subjects, using three frequency ranges (125-2000, 125-4000 and 125-8000 Hz).

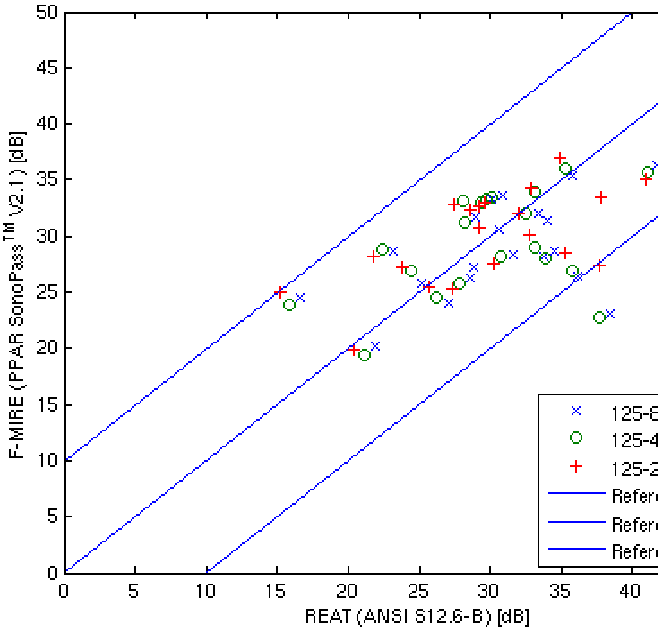

Figure 8: (Color online) Comparison between REAT and F-MIRE of the overall attenuation values of the twenty subjects with the "per-subject" approach, using the 125-2000 Hz (red '+'), 125-4000 Hz (green 'o') and 125-8000 Hz (blue 'x') frequency ranges.

It can be seen on Fig. 8 above that the best prediction is obtained when using the low-frequency range (125-2000 Hz) and that the overall prediction error is always less than 10 dB for each of the twenty cases tested.

6. CONCLUSIONS

This paper looked into the error that would be committed if the high frequencies attenuation were to be removed for the computation of several single number measurements for HPD attenuation ratings. Such calculation has been presented, for a large dataset of HPD, using various indicators (including the new Noise Reduction Level Statistics defined by ANSI S12.68-2007), for various frequency ranges.

The findings are that the absolute error never exceeding 2 dB, for all the HPD, for all single number measurements, for all the examined frequency ranges and that this error is much less than 1 dB in a very large number of cases.

Given that the discarding of theses high frequencies attenuation is actually improving the stability of the measurements made by the Field-MIRE system, it is recommended that the 4 and 8 kHz attenuation values be removed from the single number measurements values for such F-MIRE system and that there inclusion for REAT testing may worth to be reconsidered.

Future work should look into the fluctuation values of the high-frequency attenuation of an HPD, since these fluctuations appear to be really present in the occluded ear-canal system under measurement, but only "revealed" because of the high sensitivity of the F-MIRE measurement system.

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BIOGRAPHICAL SKETCH

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Jérémie Voix is an Acoustics Engineer with field experience in industrial noise reduction projects. He holds a Bachelor's degree in Fundamental Physics from *Université des Sciences et Technologies de Lille* (France) and a Master's degree in Applied Sciences in Acoustics from *Université de Sherbrooke* (Canada). He was recently awarded a Doctorate, with great distinction, from the *École de Technologie Supérieure* (Montréal, Canada), for his work on the development of a "smart earplug". Jérémie is currently working for Sonomax as CTO and Vice-President of Scientific Research and is foreseeing the day when all in-ear devices (hearing aid, hearing protector, cell phone and music player) will combine into one.

Jean Zeidan, M.Sc.
Jean Zeidan holds a Master Degree in mathematics and statistics and a Ph.D. Scholarship (Université de Montréal, Canada). He has been working for more than 26 years in the Hearing Conservation and Otologic fields and has been responsible in the past for the development of the Corti© ,Pulmo© and HPD Select© software in collaboration with Dr. Robert A. Bertrand, M.D. He worked for Sonomax from 2001 to 2008 as Senior Statistician and Information Privacy Officer. He is currently working for Bertrand Johnson Acoustics since May 2008 as Director of Scientific Research.

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