Uncertainty Calculation for Hearing Protector Noise Attenuation Measurements by REAT Method

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The objective of this paper is to quantify the uncertainty of hearing protector attenuation measurements and present the metrology study necessary for the accreditation of the Industrial Noise Laboratory (LARI) at The Federal University of Santa Catarina and Individual Protection Equipment laboratory (LAEPI) of NR consultancy Ltda. – Brazil for hearing protector noise attenuation procedures using the "Real Ear Attenuation at Threshold – REAT" method of the Brazilian National Institute of Metrology Standardization and Industrial Quality – INMETRO. A model for the calculation of measurement uncertainty was developed based on the document: "Guide to expression of uncertainty in measurement" published by the International Organization for Standardization, first edition, corrected and reprinted in 1995, Geneva, Switzerland. The uncertainty of each source of error was estimated and the overall uncertainty of the hearing protector noise attenuation measurement was calculated for each 1/1 octave band frequency and the results used in the single number (NRRsf – Noise Reduction Rating for subject fit) uncertainty calculation. It was concluded that the largest uncertainty is due to the determination of the subject hearing thresholds.

Keywords: *uncertainty, hearing protector, noise attenuation*

Introduction

Metrology is the science of measurement and it encompasses all theoretical and practical aspects related to it. For this reason, the Metrology plays an important role in quality assurance and quality measurements. High quality measurements should be based on a well-developed procedure and supported by a standardised method to assure quality control of products. The errors of measurement can be expressed by the measurement uncertainty value. This value can be used to quantify the confidence limits of the measured results and allows comparison of measurements carried out by different laboratories and for different products (INMETRO et al., 1997). Brinkmann (1988) showed that, in spite of the different methods available for noise attenuation measurements for hearing protectors (see Fig. 1), the values for the sources of errors are still not well understood and the working groups are encountering difficulties in quantifying this measurement uncertainty. This study was developed and conducted at the Vibration and Acoustics Laboratory of the Federal University of Santa Catarina, Brazil, and Individual Protection Equipment laboratory (LAEPI) of NR Consultancy Ltda., and it proposes a model for the uncertainty calculation for the hearing protector device (HPD) attenuation measurement.

Figure 1. Hearing protector devices (HPD): three earplugs (right) and two earmuffs (left).

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Nomenclature

ANSI = *American National Standards Institute;*
D/A = *Digital/Analog;*
DC = *Direct Current;*
HPD = *Hearing Protector Device;*
NRR_s = *Noise Reduction Rating for subject fit;*
PEARPA = *Program for Measurement of Hearing Protector Noise Attenuation;*
REAT = *Real Ear Attenuation at Threshold;*
$SNR_{84\%}$ = *Single Number Rating with 84% of protection;*
SPL = *Sound Pressure Level;*
Standard uncertainty – Each one of the separate contributions to uncertainty, expressed as a standard deviation;
Combined standard uncertainty – The total uncertainty resulting of combining all uncertainty components. It is equal to the positive square root of the total variance obeying the law of propagation of uncertainty;
Expanded uncertainty – It represents the interval within the measure and value is believed to lie with a specific level of confidence. It is obtained by multiplying the combined standard uncertainty by a coverage factor. For a level of confidence that equals to 95%, the coverage factor is 2;
Mensurand – Object of measurement. Quantity under interest and submitted to the measurement process (INMETRO et al., 1997);
Open threshold of hearing – The minimum effective sound pressure level that is capable of evoking an auditory sensation when the hearing protector under test is not worn (ANSI, 1997);
Closed threshold of hearing – The minimum effective sound pressure level that is capable of evoking an auditory sensation when the hearing protector under test is worn (ANSI, 1997).

REAT Measurements

The latest standard REAT method for the measurement of the noise attenuation of hearing protectors is ANSI S12.6-1997 (ANSI, 1997) (methods A and B). The measurements are carried out in each 1/1-octave band frequency from 125 to 8000 Hz (seven bands) and the results are given in the form of an average attenuation value and a standard deviation for each frequency band. These parameters are obtained from ten attenuation measurements in case of earmuffs (ten test subjects) or twenty for earplugs (twenty test subjects). The test is repeated twice for each subject and a subject average value for these trials is calculated. Each test is composed of open and closed threshold measurements (see Fig. 2). After the calculation of this mean value for each subject, these results are used to determine the overall average and its standard deviation. As can be observed, the determination of the HPD attenuation is not a direct measurement. Instead, it is calculated from the thresholds measured for all the subjects. As will be demonstrated here, this is responsible for most of the measurement uncertainty.

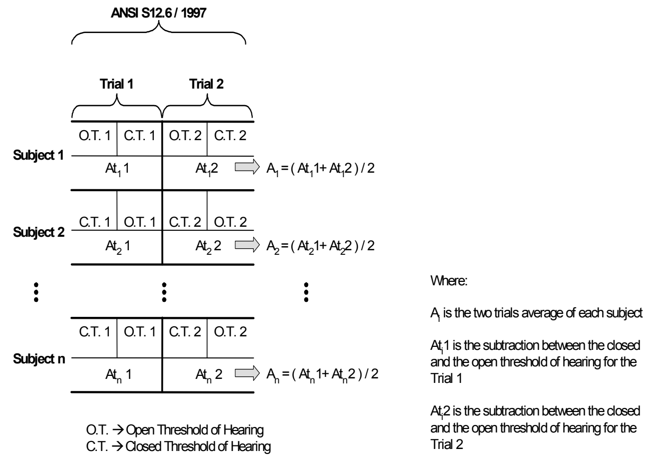

Figure 2. Method for hearing protector attenuation and standard deviation calculation.

Uncertainty Calculation

The general equation presented below is recommended by the "Guide to expression of uncertainty in measurements" (INMETRO et al., 1997) and shows the relation between the measurement uncertainty and the input parameters of the HPD attenuation. It can be written as:

$$u^2(G) = \left[\frac{\partial G}{\partial x_1}\cdot u(x_1)\right]^2 + \left[\frac{\partial G}{\partial x_2}\cdot u(x_2)\right]^2 + \cdots + \left[\frac{\partial G}{\partial x_n}\cdot u(x_n)\right]^2 \quad (1)$$

where $u(x_1)$, $u(x_2)$, …, $u(x_n)$ are the standard uncertainties of the input parameters for the attenuation measurement, $u(G)$ represents the combined uncertainty of measurements and G is the mensurand. It should be clear that Eq. (1) has to be applied to the attenuation and standard deviation equations presented in Fig. 2.

Attenuation

Considering "n" test subjects, the overall average attenuation (A_f) can be written as:

$$A_f = \frac{\sum_{i=1}^{N} A_i}{n} \quad (2)$$

$$A_f = \frac{\dfrac{(CT_{1A}-OT_{1A})+(CT_{1B}-OT_{1B})}{2} + \ldots + \dfrac{(CT_{nA}-OT_{nA})+(CT_{nB}-OT_{nB})}{2}}{n} \quad (3)$$

or

$$A_f = \frac{(CT_{1A}-OT_{1A})+(CT_{1B}-OT_{1B})+\ldots+(CT_{nA}-OT_{nA})+(CT_{nB}-OT_{nB})}{2\cdot n} \quad (4)$$

where CT_{1A} is the closed threshold value for the first trial A and the first subject; OT_{1A} is the open threshold value for the first trial A and the first subject; CT_{1B} is the closed threshold value for the second trial B and the first subject; OT_{1B} is the open threshold value for the second trial B and the first subject; CT_{nA} is the closed threshold value for the first trial A and the n-th subject; and so on.

Using Eqs. (4) and (1), then

$$u^2\left(A_f\right)=\left[\frac{1}{2\cdot n}\cdot u\left(CT_{1A}\right)\right]^2+\left[\frac{-1}{2\cdot n}\cdot u\left(OT_{1A}\right)\right]^2+\left[\frac{1}{2\cdot n}\cdot u\left(CT_{1B}\right)\right]^2+ \\ +\left[\frac{-1}{2\cdot n}\cdot u\left(OT_{1B}\right)\right]^2+\cdots+\left[\frac{1}{2\cdot n}\cdot u\left(CT_{nA}\right)\right]^2+ \\ +\left[\frac{-1}{2\cdot n}\cdot u\left(OT_{nA}\right)\right]^2+\left[\frac{1}{2\cdot n}\cdot u\left(CT_{nB}\right)\right]^2+\left[\frac{1}{2\cdot n}\cdot u\left(OT_{nB}\right)\right]^2 \tag{5}$$

Equation (5) is the general expression for the calculation of the combined standard uncertainty of the HPD noise attenuation measurement. This calculation needs the uncertainty estimation of each threshold measurement (open and closed).

Standard Deviation

Similarly, the standard deviation (Sf) can be calculated by means of:

$$S_f=\sqrt{\frac{\sum_{i=1}^{n}\left(A_i-A_f\right)^2}{n-1}}=\frac{1}{\sqrt{n-1}}\cdot\sqrt{\sum_{i=1}^{n}\left(A_i-A_f\right)^2} \tag{6}$$

or

$$S_f=\frac{1}{\sqrt{n-1}}\cdot \\ \left[\left(A_1-A_f\right)^2+\left(A_2-A_f\right)^2+\cdots+\left(A_n-A_f\right)^2\right]^{\frac{1}{2}} \tag{7}$$

where A_1, A_2, …, A_n are the average attenuations for each subject (arithmetic average of the attenuation obtained for each subject measurement).

As shown earlier, A_f is a function of A_1, A_2, ..., A_n. This implies that the derivative calculation of Eq. (7) will require a lot of mathematical work, and therefore, considering the use of the methodology presented herein and for simplicity it was considered that A_f is not a function of A_1, A_2, ..., A_n and acts like a constant. An analysis was carried out to check this assumption, which resulted in errors of less than 1%. Mathematically, the assumption can be represented by Lima (2003):

$$\frac{\partial A_f}{\partial A_i}=0 \tag{8}$$

Using Eqs. (1) and (7), it is possible to derive the general equation for the calculation of the combined standard uncertainty as:

$$u^2\left(S_f\right)=\left[\frac{\partial S_f}{\partial A_1}\cdot u\left(A_1\right)\right]^2+\left[\frac{\partial S_f}{\partial A_2}\cdot u\left(A_2\right)\right]^2 \\ +\ldots+\left[\frac{\partial S_f}{\partial A_n}\cdot u\left(A_n\right)\right]^2+\left[\frac{\partial S_f}{\partial A_f}\cdot u\left(A_f\right)\right]^2 \tag{9}$$

The partial derivative calculation of S_f in terms of A_1, A_2, ..., A_n considering the above assumption in Eq. (8), gives the following equation:

$$\frac{\partial S_f}{\partial A_i}=\frac{1}{\sqrt{n-1}}\cdot \\ \left[\left(A_1-A_f\right)^2+\left(A_2-A_f\right)^2+\cdots+\left(A_n-A_f\right)^2\right]^{-\frac{1}{2}}\cdot\left(A_i-A_f\right) \tag{10}$$

where A_i is the individual attenuation for each test subject.

Finally, the partial derivative calculation of S_f in terms of A_f is given by the following equation:

$$\frac{\partial S_f}{\partial A_f}=\frac{1}{\sqrt{n-1}}\cdot \\ \left[\left(A_1-A_f\right)^2+\left(A_2-A_f\right)^2+\cdots+\left(A_n-A_f\right)^2\right]^{-\frac{1}{2}}\cdot \\ \cdot 2\cdot\left[n\cdot A_f-\left(A_1+A_2+\cdots+A_n\right)\right] \tag{11}$$

Considering that the factor

$$\left[n\cdot A_f-\left(A_1+A_2+\cdots+A_n\right)\right]=0 \tag{12}$$

the derivative of Eq. (11) will be

$$\frac{\partial S_f}{\partial A_f}=0 \tag{13}$$

Considering the above calculation, Eq. (9) can be written as:

$$u^2\left(S_f\right)=\left[\frac{\partial S_f}{\partial A_1}\cdot u\left(A_1\right)\right]^2+\left[\frac{\partial S_f}{\partial A_2}\cdot u\left(A_2\right)\right]^2 \\ +\ldots+\left[\frac{\partial S_f}{\partial A_n}\cdot u\left(A_n\right)\right]^2 \tag{14}$$

It is clear in Eq. (14) that the determination of the standard deviation uncertainty requires the determination of the attenuation uncertainties $u(A_1)$, $u(A_2)$, ..., $u(A_n)$ of each test subject, as described in the following section.

Subject Attenuation Uncertainty

Again, the average attenuation for each subject is determined by:

$$A_i=\frac{\left(CT_{iA}-OT_{iA}\right)+\left(CT_{iB}-OT_{iB}\right)}{2} \tag{15}$$

where A_i is the average attenuation for the i-th subject.

Using Eq. (1), one obtains:

$$u^2\left(A_i\right)=\left[\frac{1}{2}\cdot u\left(CT_{iA}\right)\right]^2+\left[\frac{1}{2}\cdot u\left(OT_{iA}\right)\right]^2 \\ +\left[\frac{1}{2}\cdot u\left(CT_{iB}\right)\right]^2+\left[\frac{1}{2}\cdot u\left(OT_{iB}\right)\right]^2 \tag{16}$$

From Eq. (16), it is noticeable that the uncertainties of the open and closed hearing thresholds must be determined as follows.

Open and Closed Thresholds of Hearing Uncertainties

The determination of the open and closed hearing thresholds depends on many factors, such as: the measuring system used, measurement parameters (number of inversions, number of cycles, acoustic room characteristics, amplitude step), system calibration, subject response (HPD fitting, motivation, test experience, subjective response), variations between protectors (Guglielmone, 2003), etc.

Figure 3 represents the main factors that play an important role in the determination of the HPD attenuation uncertainty.

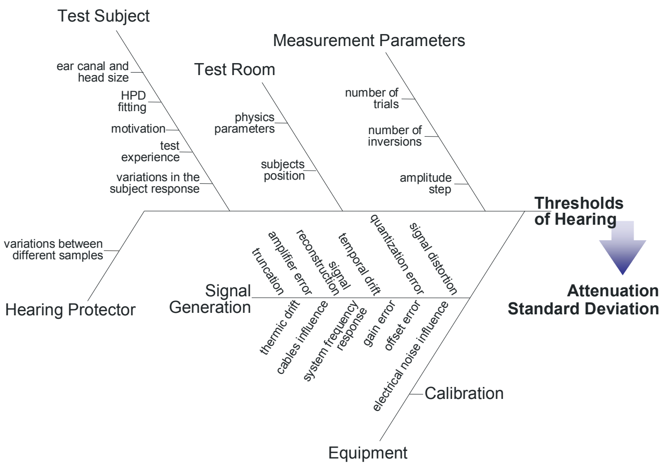

Figure 3. General list of uncertainties sources.

Considering that the factors presented in Fig. 3 are statistically independent, it is possible using Eq. (1) to determine the measurement threshold uncertainty using the following equation:

$$u_{threshold}^{2}\left(u_1, u_2, \cdots, u_n\right) = u_1^2 + u_2^2 + \cdots + u_n^2 \tag{17}$$

where u_1, u_2, ..., u_n are the uncertainties of the above mentioned factors.

With the results obtained from Eqs. (5), (14), (16) and (17), it is now possible to estimate the HPD attenuation measurement uncertainty.

NRR_{SF} Uncertainty Calculation

A consequence of the equations presented above is the fact that is possible to use the results obtained through these equations in the calculation of the NRR_{SF} uncertainty as presented below.

The NRR_{SF} value is given by Gerges (1992):

$$NRR_{SF} = SNR_{84\%} - 5 \tag{18}$$

Applying again Eq. (1), one writes:

$$u^2(NRR_{SF}) = \left[\frac{\partial NNR_{SF}}{\partial SNR_{84\%}} \cdot u\left(SNR_{84\%}\right)\right]^2 \tag{19}$$

The partial derivative above is equal to unity and the uncertainty of the *NRRSF* measurement can be defined as:

$$u(NRR_{SF}) = u\left(SNR_{84\%}\right) \tag{20}$$

Therefore, the determination of the NRR_{SF} uncertainty involves the calculation of $SNR_{84\%}$ uncertainty. The definition of $SNR_{84\%}$ is (Gerges, 1992):

$$\begin{aligned} SNR_{84\%} = 100\text{ dB} - 10\cdot log\, \Big\{ & 10^{0.1\cdot[75.4-(A_{125}-a\cdot SD_{125})]} + 10^{0.1\cdot[82.9-(A_{250}-a\cdot SD_{250})]} + \\ & + 10^{0.1\cdot[88.3-(A_{500}-a\cdot SD_{500})]} + 10^{0.1\cdot[91.5-(A_{1000}-a\cdot SD_{1000})]} + 10^{0.1\cdot[92.7-(A_{2000}-a\cdot SD_{2000})]} + \\ & + 10^{0.1\cdot[92.5-(A_{4000}-a\cdot SD_{4000})]} + 10^{0.1\cdot[90.4-(A_{8000}-a\cdot SD_{8000})]} \Big\} \end{aligned} \tag{21}$$

where A_i and SD_i are the attenuation and standard deviation for each frequency band i.

Using Eq. (21), it can be noted that the value of $SNR_{84\%}$ depends only on the average attenuation and standard deviation for each test frequency band. Its uncertainty can be calculated by:

$$\begin{aligned} u^2(SNR) = & \left[\frac{\partial SNR}{\partial A_{125}}\cdot u(A_{125})\right]^2 + \left[\frac{\partial SNR}{\partial SD_{125}}\cdot u(SD_{125})\right]^2 + \\ & + \left[\frac{\partial SNR}{\partial A_{250}}\cdot u(A_{250})\right]^2 + \left[\frac{\partial SNR}{\partial SD_{250}}\cdot u(SD_{250})\right]^2 \\ & + \ldots + \left[\frac{\partial SNR}{\partial A_{8000}}\cdot u(A_{8000})\right]^2 + \left[\frac{\partial SNR}{\partial SD_{8000}}\cdot u(SD_{8000})\right]^2 \end{aligned} \tag{22}$$

The following transformation is now introduced to simplify the equations:

$$\begin{aligned} X = & 10^{0.1\cdot[75.4-(A_{125}-a\cdot SD_{125})]} + 10^{0.1\cdot[82.9-(A_{250}-a\cdot SD_{250})]} + \\ & + 10^{0.1\cdot[88.3-(A_{500}-a\cdot SD_{500})]} + 10^{0.1\cdot[91.5-(A_{1000}-a\cdot SD_{1000})]} \\ & + 10^{0.1\cdot[92.7-(A_{2000}-a\cdot SD_{2000})]} + 10^{0.1\cdot[92.5-(A_{4000}-a\cdot SD_{4000})]} \\ & + 10^{0.1\cdot[90.4-(A_{8000}-a\cdot SD_{8000})]} \end{aligned} \tag{23}$$

Using the Eq. (23) and carrying out some mathematical simplification, the partial derivatives of Eq. (22) are written for each frequency band as:

$$\frac{\partial SNR}{\partial A_{125}} = \left(\frac{1}{X}\right)\cdot\left\{10^{0.1\cdot[75.4-(A_{125}-a\cdot SD_{125})]}\right\} \tag{24}$$

$$\frac{\partial SNR}{\partial SD_{125}} = \left(-\frac{a}{X}\right)\cdot\left\{10^{0.1\cdot[75.4-(A_{125}-a\cdot SD_{125})]}\right\} \tag{25}$$

Similar equations for the 1/1 octave frequency band at 250, 500, 1000, 2000, and 4000 Hz numbered (26) to (34).

$$\frac{\partial SNR}{\partial A_{8000}} = \left(\frac{1}{X}\right)\cdot\left\{10^{0.1\cdot[90.4-(A_{8000}-a\cdot SD_{8000})]}\right\} \tag{26}$$

$$\frac{\partial SNR}{\partial SD_{8000}} = \left(-\frac{a}{X}\right)\cdot\left\{10^{0.1\cdot[90.4-(A_{8000}-a\cdot SD_{8000})]}\right\} \tag{27}$$

To get the uncertainty equation for the standard deviation, the equations above must be inserted into Eq. (22).

Case Study

In order to check the methodology presented above, it was applied to a hearing protector (earplug) measurement using ANSI S12.6 (ANSI, 1997), subject fit method (twenty test subjects). Similar calculation can be carried out if using other standard: ISO 4869-1 (ISO, 1990). The system used for this measurement is presented in Fig. 4. To calculate the uncertainty of each threshold according to Eq. (17), the following factors were considered: amplitude step (measurement parameters), system calibration error (equipment), amplifier gain error (equipment), signal truncation (equipment), quantization error from digital-analog (D/A) conversion (equipment), electric and thermal noise from the analog output board used in the measurement system (equipment), subject response variation (test subject). Each of these factors is addressed in the following sections. Other uncertainties were estimated but subsequently disregarded since their contribution to the overall uncertainty was negligible, for the reasons given below. It is important to mention again that these factors change for each HPD test and each measurement system used.

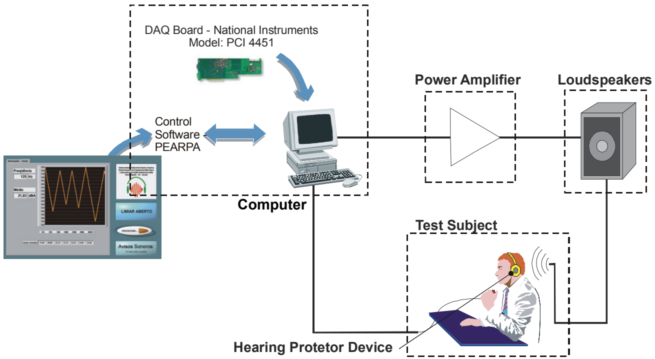

Figure 4. Measurement system used in the case study.

Amplitude Step

According to ANSI S12.6 (ANSI, 1997), the amplitude step variation shall be defined within the interval from 1.0 dB to 2.5 dB. With the aim of investigating the amplitude step, which corresponds to the least standard deviation (least uncertainties), 312 open hearing thresholds (3 trials with 4 amplitude steps in 26 test subjects) were performed. Some results are presented in Fig. 5, which shows the average standard deviation as a function of frequency bands for the four choices of amplitude step. Duncan's multiple range tests (Johnson, 1994) were conducted to check if the differences shown in Fig. 5 are statistically significant.

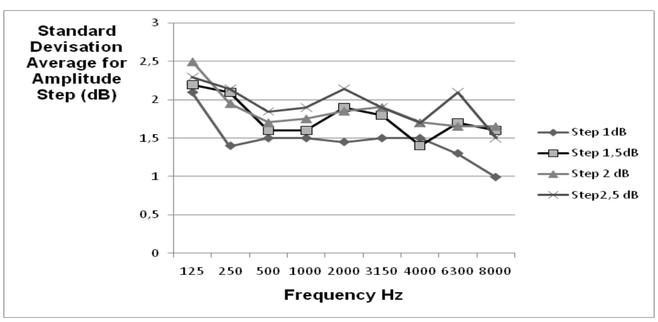

Figure 5. Standard deviation average for the step increment.

The amplitude step of 1.0 dB was considered to give the least standard deviation and consequently the least uncertainty (Lima, 2003). Its uncertainty was estimated as ±0.5 dB with a rectangular distribution. It should be noted that this type of distribution is widely employed in other metrology fields (dimensional applications), when there is no knowledge regarding the type of distribution that best represents the phenomena. This recommendation is considered a conservative approach (INMETRO et al. 1997).

Calibration

Since the measurement system under study has two different measuring ranges for signal generation, calibrations were performed in both ranges. Figure 6 shows the system used to calibrate the measurement system employed in HDP tests. It relates the voltage generated by the measurement system to the sound pressure level at the reference point inside the test room. The equipment used for the calibrations was: Brüel & Kjaer Pulse 7700 analyzer, ½" pressure microphone, National Instruments digital acquisition and generation board model PCI 4451, specific module inside PEARPA software for calibration, loudspeakers for noise generation and a power amplifier to drive the loudspeakers.

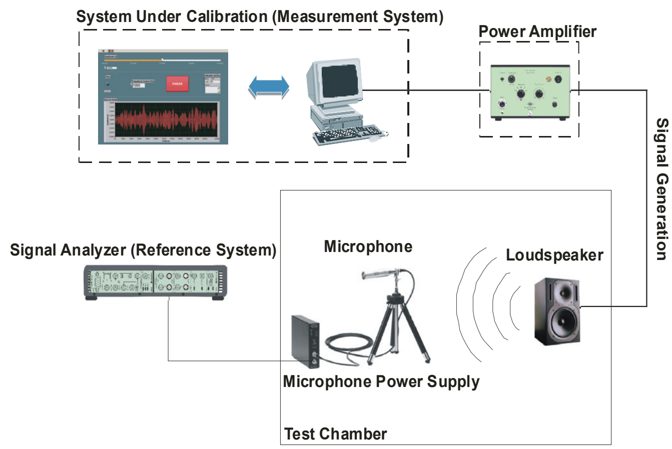

Figure 6. Calibration setup.

A regression model using the least squares method was developed to represent the calibration curve. The uncertainty contribution from each frequency band due to calibration was calculated from the maximum variation of SPL due to the residual errors of the regression fitting. A rectangular distribution was used and the calibration uncertainty values (rounded to four decimal places) are presented in Tab. 1.

Table 1. Calibration uncertainty values.

Threshold (dB)	Frequency (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
Open	0.44	0.54	0.17	0.20	0.30	0.71	0.73	0.23	0.59
Closed	0.43	0.21	0.05	0.39	0.11	0.25	0.45	0.25	0.12

Signal Generation

Since the signal generated is produced mainly by the data acquisition/generation board (PCI-4451 by National Instruments) most of the sources of errors presented below are related to it.

Offset Error

The residual voltage present in amplifiers and converters can produce some errors in the signal generated by the measurement system. Since loudspeakers are not sensitive to DC signals, this source of error was disregarded.

Gain Error

The behavior of a real amplifier differs from that used under ideal conditions. The real gain of this amplifier is not the same as the designed gain. This difference can produce errors in the signal generation process. Theoretically, this kind of influence should be corrected with a calibration procedure. However, according to the data from the manufacturer, the amplifier present in the PCI 4451

(D/A board used in this study) has a gain error of ± 0.1 dB even after this procedure. For this reason a value of ± 0.1 dB was used to estimate the uncertainty due to the gain error. As the board manufacturer provided no information about the distribution, a rectangular distribution was considered for the calculations.

Signal Truncation

The data to be generated are created from mathematical operations carried out by computer. Since the digital data used in these operations do not have an infinitesimal resolution, these data are often rounded to the next digital value. This rounding produces an error called truncation. In the measurement system, the uncertainty due to truncation was estimated to be ± 0.005 dB with a rectangular distribution.

Quantization Error

Every time a D/A conversion is performed an error is produced since the conversion process is not ideal. This non-ideality is called quantization error and it is dependent on the board resolution and the measuring range used. The board manufacturer suggests the following equation to estimate the quantization error produced by this kind of board:

$$QE = \frac{MR}{2^{NB} - 1} \tag{28}$$

where QE is the quantization error in volts; MR is the measuring range used in the board (software selectable); NB is the number of bits of the board (resolution).

Applying Eq. (28) to the measuring ranges used in the open and closed threshold determination yields:

$$QE_{CT} = \frac{MR_{CT}}{2^{NB} - 1} = \frac{2}{2^{16} - 1} \cong 0.0305 mV \tag{29}$$

$$QE_{OT} = \frac{MR_{OT}}{2^{NB} - 1} = \frac{0.2}{2^{16} - 1} \cong 0.00305 mV \tag{30}$$

where the indices CT and OT represent the Closed Threshold and the Open Threshold, respectively.

The results given above are not adequate because they are expressed in volts, and a propitious result should be expressed in decibels. Since the regression models used are in the exponential form, these values produce different errors according to the sound pressure levels that are generated. If the sound pressure level is low, the quantization error causes a larger uncertainty than when the sound pressure level is higher. To consider this fact, the uncertainty values for the quantization error were calculated from

$$u_{QE} = \pm \left| SPL_{REAL} - \left| \left(SPL_{+QE} ; SPL_{-QE} \right) \right|_{Max} \right| \tag{31}$$

where SPL_{REAL} is the sound pressure level produced by a voltage V; SPL_{+QE} is the sound pressure level produced by a voltage equal to ($V+QE$); SPL_{-QE} is the sound pressure level produced by a voltage equal to ($V-QE$).

To calculate the sound pressure levels mentioned above, the regression models obtained in the calibration processes were used:

$$SPL = \frac{ln\left(\frac{V}{A}\right)}{B} \tag{32}$$

where V is the voltage in volts produced in the board terminals; A and B are the regression model constants and SPL is the sound pressure level caused by the voltage V at the reference point (a white noise filtered in third octave bands was used). The values of A and B change for each frequency test.

With the equations presented in (31) and (32) it is possible to estimate the uncertainty for each threshold and each test frequency. A rectangular distribution was adopted.

Noise Error

The board used for signal generation (PCI-4451) is placed in an environment with much interference like video boards, sound boards, hard disks. These components are responsible for electric noise that causes interferences in the original signal. According to the manufacturer, the uncertainties caused by this interference have maximum values that can be estimated by:

$$E_{Electric\,Noise} = \pm 1.0 \cdot LSB \cdot SA \tag{33}$$

where $E_{Electric\,Noise}$ is the error due to electrical noise; LSB is the least significant bit; SA is the signal amplitude in volts.

For the same reason explained earlier, an uncertainty expressed in volts can not be used in the global uncertainty calculation. To transform this voltage variation into sound pressure level variation, the following equation was used:

$$u_{Electric Noise} = \pm \left| SPL_{REAL} - \left| \left(SPL_{+Electric Noise} ; SPL_{-Electric Noise} \right) \right|_{Max} \right| \tag{34}$$

The equation presented above is similar to Eq. (31), and the values of SPL_{REAL}, $SPL_{+Electric\ Noise}$, and $SPL_{-Electric\ Noise}$ can also be estimated by Eq. (32). A rectangular distribution was adopted.

Thermal Drift

According to the manufacturer, when the board used for signal generation (PCI-4451) is used in the temperature range from 0ºC to 40ºC, it is not necessary to consider the influence of thermal drifts. As the equipment operates in this range, this source of error was neglected.

Temporal Drift

Small variations in the board behavior during usage can lead to errors. The aging processes become less critical with time since the components present in the board become more stable. For measurements taken within 24 hours of the calibration process, temporal drift can be disregarded. After this period, the manufacturer suggests that an uncertainty of ±15 parts per million should be considered. The following equation was used to estimate the uncertainty due to temporal drift. A rectangular distribution was considered.

$$u_{Temporal\ Drift} = \pm \left| SPL_{REAL} - \left| \left(SPL_{+Temporal\ Drift} ; SPL_{-Temporal\ Drift} \right) \right|_{Max} \right| \tag{35}$$

Frequency Response Function

The system frequency response is not flat. If calibration is not performed, this effect can cause a change in the signal amplitude in some frequency test bands. For the case study presented, the calibration was performed and the influence of this factor was minimized. As a consequence, this source of error was not considered.

Cables Influence

Cables either function well or not at all. In case of damaged cable, this is easily detected and solved. In the case of functioning cable, this can be modeled as electric components of low resistivity. This resistivity can affect the results (amplitude and frequency variations) if the calibration process is not performed. Since the system was calibrated this source of error was considered indirectly.

Power Amplifier

The power amplifier used to drive the loudspeakers has two major sources of influence: harmonic distortion and electric noise. The influence of the harmonic distortion is too small (less than 0.01% – typical) to be considered. The electric noise was measured to check its levels. The influence of the electric noise is also negligible since it manifests only in the 50~60 Hz (major influence, but also small) and its sub harmonics (minor influence). This factor was, therefore, not considered in the uncertainty calculation.

Signal Distortion

According to the manufacturer, the signal distortion produced by the board is less than the distortion produced by the power amplifier and it was hypothesized that the board has no significant influence in the signal generation process. For the same reasons, this factor was not considered in the uncertainty calculation.

Signal Reconstruction

The analogical signal reconstructed from digital data should ideally have finite amplitude and temporal width equal to zero. Most of the D/A converters maintain a constant voltage in the board terminals until the next sample changes its value, producing an output signal that can be modeled as a series of pulses with variable amplitude.

According to the manufacturer, this non-ideality produces an error that can be modeled by:

$$E_{Amplitude} = \frac{sin\left(\frac{\pi \cdot f}{f_S}\right)}{\frac{\pi \cdot f}{f_S}} \cdot A \tag{36}$$

where A is the signal amplitude; f is the signal frequency; f_S is the sample frequency used for generation.

In order to minimize this kind of error, the PCI 4451 has circuits that re-sample the signal with a frequency eight times the original sample frequency. On the other hand, using Eq. (36), it is possible to note that the error is minimized when the sample frequency is higher.

These two pieces of information combined were used to estimate the uncertainty contribution due to the signal reconstruction error at the most critical test band (8000 Hz). The calculation showed that the error is below 0.01%. Since its value is small when compared to the other sources of error, this factor was disregarded.

Variation in the Subject Response

As explained earlier, subjects are needed in order to perform HPD attenuation measurements. The attenuation is a function of the difference between the open and closed hearing thresholds for all the test subjects. The test subject responses are influenced by many factors such as mood, attention, capacity of concentration, ear canal and head size, test experience, ambient pressure and temperature. To estimate this uncertainty it was considered that the hearing thresholds lay between two limits: the maximum peak and the minimum valley of the subject trace. Thus, the mean threshold will be situated at any point between these two limits with the same probability.

The hypothesis above can be modelled by a rectangular distribution with width equal to "r", where "r" is defined as half of the distance between the highest peak and the lowest valley in the trace, as can be observed in Fig. 7. It is important to mention that the scale in the graph of Fig. 7 is inverted because it follows the same standards used in audiometers.

Other Uncertainties

The measurements were carried out in only one reverberation room qualified according to ANSI S12.6-1997(2000). Therefore, the uncertainty due to reverberation room characteristics was not considered. Since this room is qualified, it is expected that this uncertainty can be neglected.

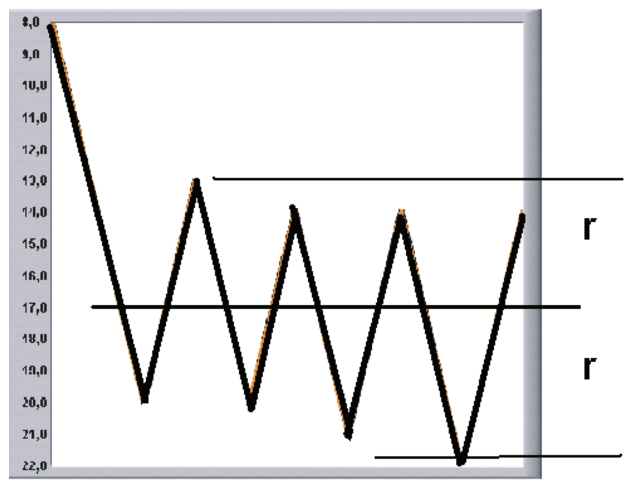

Figure 7. Level-time domain distribution adopted in the variation in the subject response uncertainty.

Uncertainty Calculation

In order to estimate the uncertainty for the measurement, it is necessary to calculate the uncertainties of each threshold. Since this procedure would be exhaustive if it were presented for each threshold (considering that at least twenty test subjects (plug HPD) are required for each HPD attenuation measurement and each subject produces twenty-eight hearing thresholds (two open and two closed at seven different test frequencies, 7 x 4 = 28), the total number of thresholds would be 560), the uncertainty calculation is demonstrated for just one hearing threshold selected randomly (12th subject at 4000 Hz test frequency, first trial, open threshold).

The values of each source of uncertainty, presented in Eq. (17), are given in Tab. 2.

Table 2. Calculation of the combined uncertainty of the first cycle of the open threshold measurement of the 12th subject at 4000 Hz test frequency.

SOURCE		ESTIMATED VALUE	DISTRIBUITION	DIVISOR	STANDARD UNCERTAINTY
Amplitude Step	u_{amp}	0.50	Rectangular	$\sqrt{3}$	0.288675
Truncation	u_{trunc}	0.005	Rectangular	$\sqrt{3}$	0.00288675
Calibration Error	u_{cal}	0.7314	Rectangular	$\sqrt{3}$	0.422274
Amplifier gain error	u_{gain}	0.10	Rectangular	$\sqrt{3}$	0.057735
Quantization error	u_{quant}	0.4407433	Rectangular	$\sqrt{3}$	0.254463
Electric noise	u_{noise}	1.8949E-10	Rectangular	$\sqrt{3}$	1.09402E-10
Temporal drift	u_{temp}	9.1688E-10	Rectangular	$\sqrt{3}$	5.29363E-10
Variation in subject response	$u_{subj.resp.}$	8.25	Rectangular	$\sqrt{3}$	4.76314
$u_{treshold} = [(u_{amp})^2+(u_{trunc})^2+(u_{cal})^2+(u_{gain})^2+(u_{quant})^2+(u_{noise})^2+(u_{temp})^2+(u_{subj.resp.})^2]^{½}$					4,77976 dB(A)

Table 2 represents the calculation of the combined uncertainty of the first trial of the open threshold measurement, of specific subject (12th), at 4 kHz. From this table, it can be observed that the major influence is due to the variation of the subject response for this particular threshold. Actually, the behaviour presented above repeats for the other thresholds and suggests that the variation of the subject response is really the greatest source of error in the HPD attenuation measurement.

Figure 8 shows the top five average values for the threshold uncertainties for all thresholds, trials, subjects and frequencies. It was calculated by the following way:

1. for each threshold, frequency and subject the uncertainties of each source of error (calibration, subject response, amplitude step) were estimated; 4480 uncertainties were estimated in this step (20 subjects x 4 thresholds x 7 frequencies x 8 sources of error);
2. the average value was taken for each source of error and frequency reducing the 4480 original values to 56 (4480 divided by 20 subjects x 4 thresholds)
3. the average value was taken for each source of error again and the final results are the results presented in Fig. 8 (56 divided by 7 frequencies). The smaller sources of error (truncation, electric noise and temporal drift) were not plotted.

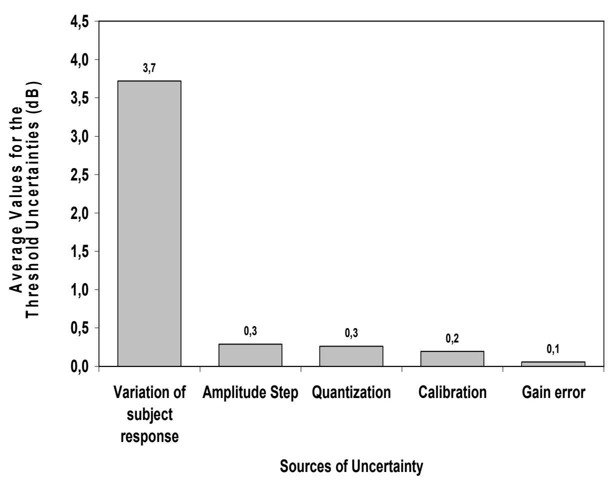

Figure 8. Average threshold uncertainty for the top sources.

After the calculation of the uncertainty values for each threshold, the calculation of the uncertainty for each test subject according to Eq. (16) is performed and the global uncertainty of the attenuation and the standard deviation – Eqs. (5) and (14), respectively – were calculated.

The overall results, rounding the values to two decimals places, are presented in Tab. 3:

Table 3. Hearing protector device measurement result, combined standard uncertainty and expanded uncertainty.

INPUT QUANTITY	FREQUENCY (Hz)						
	125	250	500	1000	2000	4000	8000
Attenuation (dB)							
Measurement Result	18.17	20.46	24.88	23.94	30.87	37.53	37.73
Combined Standard Uncertainty	0.94	0.90	0.88	0.82	0.82	0.85	0.85
Expanded Uncertainty (p = 95.45%)	1.87	1.79	1.76	1.65	1.65	1.71	1.70
Standard Deviation (dB)							
Measurement Result	7.30	8.17	8.42	6.43	5.20	6.27	8.18
Combined Standard Uncertainty	0.97	0.85	0.88	0.75	0.83	0.79	0.81
Expanded Uncertainty (p = 95.45%)	1.95	1.70	1.76	1.50	1.66	1.57	1.63

Finally, using the values calculated above and applying them in Eqs. (20) and (22) it is possible to obtain the uncertainty of NRR_{SF} and $SNR_{84\%}$. These results are presented in Tab. 4 (the results are rounded to two decimals places).

Table 4. Application of the hearing protector device measurement result in the determination of the NRR_{SF} and $SNR_{84\%}$ uncertainties.

INPUT QUANTITY	RESULTS
SNR84% (dB)	
Measurement Result	22.06
Combined Standard Uncertainty	0.60
Expanded Uncertainty (p = 95,45%)	1.20
NRRSF (dB)	
Measurement Result	17.06
Combined Standard Uncertainty	0.60
Expanded Uncertainty (p = 95.45%)	1.20

Discussions and Conclusion

The methodology presented in this paper reveals that the calculation of the hearing protector noise attenuation uncertainty is long and arduous because it involves a lot of information. The values presented here are a small portion of the data generated by the formulas shown above.

The uncertainty due to the subject response is the major source of error, accounting for nearly 80% of all sources of error. The sources of uncertainty due to the equipment are small when compared to the subject response. The “amplitude step”, “quantization” and “calibration” appear to have similar contributions to the system studied here. This fact was already expected as mentioned in literature (Brinkmann & Richter, 1986) (Brinkmann, 1988) (Royster et al., 1996).

To check the consistence of the models developed, a new measurement was made and its uncertainties were estimated and compared with the measurement shown above. The results of this comparison can be observed in Fig. 9.

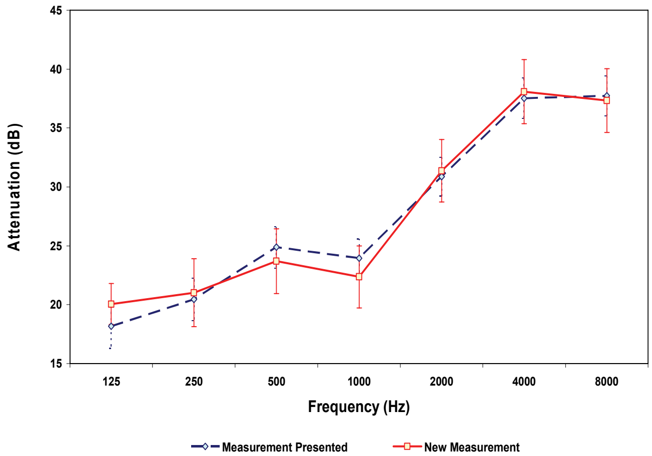

Figure 9. Comparison between two measurements made with the same HPD.

The curves display the measurement results plotted with the uncertainty values presented in Tab. 3. It is clearly shown that the uncertainties and the measurement results are in good agreement at higher frequencies (2 to 8 kHz). In the middle frequency region (500 to 1000 Hz) the measurement results are not in such good agreement, but the uncertainty limits are consistent. Only in the 125 Hz frequency band the uncertainty limits appear to be underestimated suggesting that, for this specific frequency, there must be some source of uncertainty that was disregarded or underestimated.

Another interesting conclusion is that the high number of test subjects in the measurements seems to compensate the wide dispersion in the values for the hearing thresholds, so that the overall uncertainties remain within reasonable values, around 1.5 to 2.0 dB.

This paper is a first attempt in the development of new methodologies for uncertainty estimation for hearing protector attenuation measurements. In this case study some sources of uncertainty were not considered separately. These sources of uncertainty were grouped as can be observed in the variation of subject response. In this case, the effects of fitting, ear canal, head size, test experience, mood, attention, capacity of concentration, ambient conditions were all considered together.

Acknowledgments

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