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# UNCERTAINTY FOR NOISE ATTENUATION MEASUREMENTS OF HEARING PROTECTORS BY REAT METHOD

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**Abstract:** The objective of this paper is to present a model for the calculation of measurement uncertainty for noise attenuation measurements of hearing protector by REAT method. The uncertainty calculation was based on the document: "Guide to expression of uncertainty in measurement" by the International Organization for Standardization, first edition, corrected and reprinted in 1995, Geneva, Switzerland. The uncertainty of each source of error was estimated. The overall uncertainty of the noise attenuation measurement of hearing protectors was calculated for each 1/1 octave band frequency test and the results applied in the single number ($NRR_{SF}$ - Noise Reduction Rating for subject fit) uncertainty calculation.

**Keywords:** hearing protectors, noise attenuation

## 1. REAT MEASUREMENTS

The latest standard REAT method for the measurement of the noise attenuation of hearing protectors is ANSI S12.6-1997 (methods A and B)[1]. The measurements are carried out in each 1/1 octave band frequency test from 125 to 8000 Hz (seven 1/1 octave bands) and the results are given in the form of an average attenuation value and standard deviation for each frequency band and NRRsf single number. These parameters are obtained from ten attenuation measurements for earmuffs (ten test subjects) or twenty attenuation measurements 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 Figure 1). After the calculation of this median 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 it will be demonstrated here, this fact is responsible for most of the measurement uncertainty.

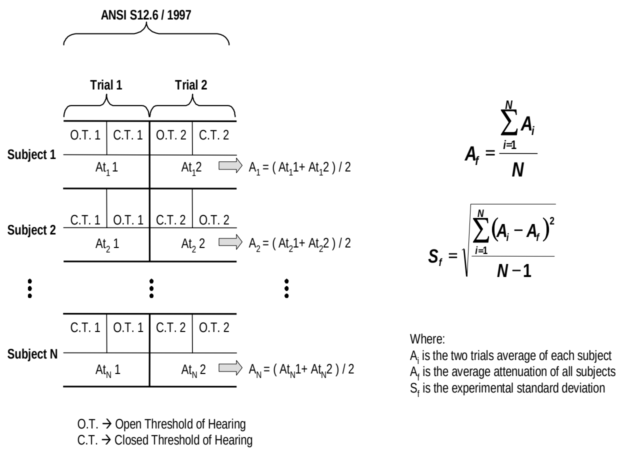


Figure 1: Method for hearing protector Attenuation and Standard Deviation calculation

## 2. UNCERTAINTY CALCULATION

The following general equation shows the relation between the measurement uncertainty and the input parameters of the HPD attenuation [6]:

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

Where $u(x_1)$, $u(x_2)$,…, $u(x_n)$ are the standard uncertainty of the input parameters for the attenuation measurement and u(G) represents the combined uncertainty of measurements. It should be clear that equation (1) has to be applied to the attenuation and standard deviation equations presented in Figure 1.

## 3. ATTENUATION

The Considering “n” test subjects, the overall average attenuation ($A_f$) can be written as:

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

Using equations (2), the combined standard uncertainty Is given by:

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

(3)

Equation (3) above is the general expression for the calculation of combined standard uncertainty of the HPD noise attenuation. This calculation needs the uncertainty estimation of each of the threshold measurements (open and closed).

## 4. STANDARD DEVIATION

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

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

(4)

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

(5)

where $A_1, A_2, \ldots , A_n$ are the average attenuation of each subject (arithmetic average of the attenuation obtained for each subject measurement).
As shown by the previous equation, $A_f$ is a function of $A_1, A_2, \ldots, A_n$. This implies that the derivative calculation of the equation (5) needs some mathematical treatment, and therefore, for simplicity it was considered that $A_f$ is not a function of $A_1, A_2, \ldots, A_n$ and it acts like a constant. An analysis was carried out with mathematical software to check this assumption, which gave errors of less than 1%. Mathematically, the assumption can be represented by:

$$\frac{\partial A_f}{\partial A_i} = 0 . \qquad (6)$$

Using equations (1) and (5), it is possible to derive the general equation for the calculation of the standard combined uncertainty as:

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

(7)

The partial derivative calculation of $S_f$ in terms of $A_1, A_2, \ldots, A_n$ considering the above assumption In equation (6), gives the following equation:

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

(8)

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:

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

(9)

To determine the value of this equation it is possible to consider that:

$$\left[ n \cdot A_f - (A_1 + A_2 + \cdots + A_n) \right] = 0 \, ,$$

(10)

and the value of the derivative will be:

$$\frac{\partial S_f}{\partial A_f} = 0 \, . \qquad (11)$$

Considering the above, equation (7) can be written as:

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

(12)

It is clear in equation (12) that the determination of the standard deviation uncertainty, requires the determination of the attenuation uncertainty $u(A_1)$, $u(A_2)$, ..., $u(A_n)$ of each test subject.

**5. SUBJECT ATTENUATION UNCERTAINTY**

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

$$A_i = \frac{(CT_{iA} - OT_{iA}) + (CT_{iB} - OT_{iB})}{2} \, ,$$

(13)

where $A_i$ is the average attenuation of the *i*-th subject. Using equation (1):

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

(14)

From equation (14), it is obvious that the uncertainties of the open and closed hearing thresholds must be determined.

**6. 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, measurements parameters (number of inversions, number of cycles, acoustic room characteristics, amplitude step, etc), system calibration, subject response (HPD fitting, motivation, test experience, subjective response, etc.), variations between protectors sample, etc. Figure 2 represents the main factors that play an important role in the determination of the HPD attenuation uncertainty.

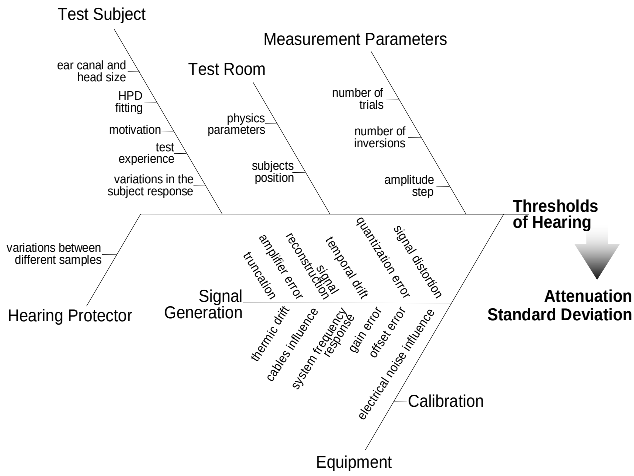


**Figure 2: General List of Uncertainties Sources**

Considering that the factors presented in Figure 2 above are statistically independent, it is possible, using equation (1), to determine the measurement threshold uncertainty using the following equation:

$$u^2_{threshold}(u_1, u_2, \cdots, u_n) = u_1^2 + u_2^2 + \cdots + u_n^2 \, ,$$

(15)

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

Now with the results obtained from equations (15), (14), (12) and (3) it is possible to estimate the HPD attenuation measurement uncertainty.

**7. $NRR_{SF}$ UNCERTAINTY CALCULATIONS**

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

The $NRR_{SF}$ value is given by:

$$NRR_{SF} = SNR_{84\%} - 5 \qquad (16)$$

Applying again equation (1):

$$u^2(NRR_{SF}) = \left[ \frac{\partial NNR_{SF}}{\partial SNR_{84\%}} \cdot u(SNR_{84\%}) \right]^2 \quad (17)$$

The partial derivative above is equal to unity and the uncertainty of the $NRR_{SF}$ measurement could be defined as:

$$u(NRR_{SF}) = u(SNR_{84\%}) \quad (18)$$

Therefore, the determination of the $NRR_{SF}$ uncertainty involves the calculation of $SNR_{84\%}$ uncertainty.
To get the uncertainty equation for the standard deviation, the equations above must be inserted into equation.

## 8. CASE STUDY

In order to check the methodology presented above, it was applied in a plug hearing protector measurement using ANSI S12.6 – 1997 (B), subject fit method (twenty test subjects). The system used for this measurement is presented in Figure 3. To calculate the uncertainty of each threshold [equation (15)], 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 card used in the measurement system (equipment), subject response variation (test subject). 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 from each HPD test and each measurement system used.

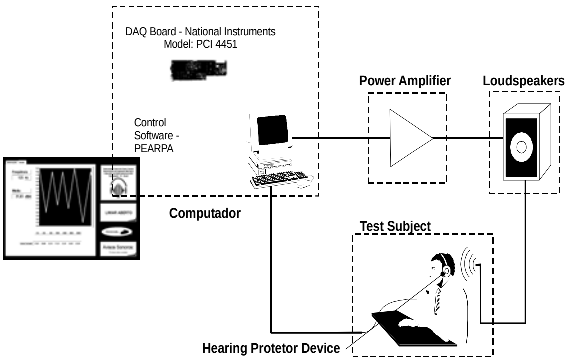


Figure 3: Measurement System used in the case study

### 8.1. Amplitude Step

According to ANSI S12.6 – 1997 (B), the amplitude step 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 Figure 4 which shows the standard deviation average as a function of frequency bands for the four choices of amplitude step. Multiple range tests were conducted to check if the differences shown in Figure 4 are statistically significant.
The amplitude step of 1.0 dB was considered to give the least standard deviation and consequently the least uncertainty [2]. Its uncertainty was estimated as ±0.5 dB with a rectangular distribution.

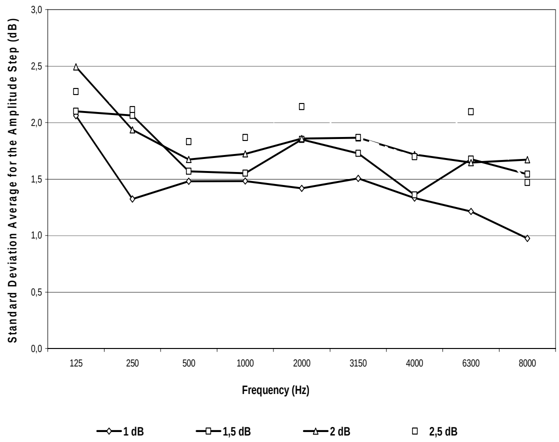


**Figure 4: Standard Deviation Average for the Step Increment**

### 8.2. Calibration

Since the measurement system under study has two different measuring ranges for signal generation, the calibration were performed in both ranges. Figure 5 shows the system used to calibrate the measurement system employed in HDP tests. It relates the tension generated by the measurement system to the sound pressure level at the reference point inside the test room. The equipment used for the calibration were: Brüel & Kjaer pulse analyzer 7700, ½"pressure microphone, National Instruments digital acquisition and generation card model PCI 4451, specific software for calibration (PEARPA), loudspeakers for noise generation and a power amplifier to supply the loudspeakers.

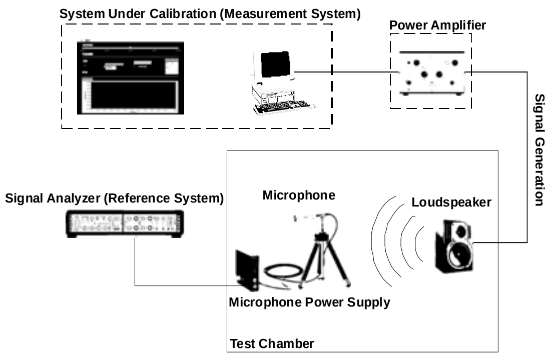


**Figure 5: Calibration set-up**

**Table 1: Calibration Uncertainty Values**

| Threshold | Frequency (Hz) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 125 | 250 | 500 | 1000 | 2000 | 3150 | 4000 | 6300 | 8000 |
| Open Threshold (dB) | 0.4 | 0.5 | 0.2 | 0.2 | 0.3 | 0.7 | 0.7 | 0.2 | 0.6 |
| Closed Threshold (dB) | 0.4 | 0.2 | 0.04 | 0.4 | 0.1 | 0.2 | 0.4 | 0.2 | 0.1 |

***8.3. Signal Generation***

The sources of errors such as offset error, gain error, signal truncation, quantization error, thermal drift and temporal drift are quantified (see table 2) from the signal generation data acquisition/generation board (PCI-4451 by National Instruments) data sheet.

***8.4. Variation in the Subject Response***

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 as mood, attention, capacity of concentration, ear canal and head size, test experience, etc. These factors are together responsible for different subject responses under similar conditions (pressure, temperature, same HPD, etc.) and these differences generate another source of error.

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 median threshold will be situated at any point between these two limits with the same probability. The hypothesis above can be modeled by a rectangular distribution with width equal to “a”, where “a” is define as half of the distance between the highest peak and the lowest valley in the trace, as can be observed in Figure 6.

It is important to mention that the scale in the graph of

Figure is inverted because it follows the same standards used in audiometers.

***8.5. Other Uncertainties***

The HPD attenuation measurement has other sources of errors beyond those presented above like: HPD fitting, variation between HPD samples, test room parameters, etc. These factors were not considered in the uncertainty calculation because it was hypothesized that their influence is very small and does not affect the results as much as the others factors presented in this case study.

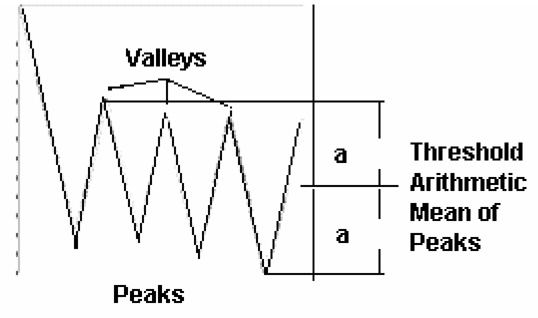


Figure 6: Distribution adopted in the Variation in the Subject Response uncertainty

***8.6. 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 shown for each threshold, the uncertainty calculation is demonstrated for just one hearing threshold selected ($12^{th}$ subject at 4000 Hz, first trial, open threshold). The values of each source, presented in Equation (15), are given in table 2. 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 behavior 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. After the calculation of the uncertainties values for each threshold, the calculation of the uncertainty of each test subject according to equation (14) is performed and the global uncertainty of the attenuation and the standard deviation are calculated from equations (3) and (12) respectively . Table 3 shows the overall values final values. Applying then equations (18) and (20) it is possible to obtain the uncertainty of $NRR_{SF}$ and $SNR_{84\%}$. These results are presented in table 4.

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 | $\sqrt{3}$ | 0.28 |
| Truncation | $u_{trunc}$ | 0.00 | Rectangular | $\sqrt{3}$ | 0.00 |
| Calibration Error | $u_{cal}$ | 0.73 | Rectangular | $\sqrt{3}$ | 0.42 |
| Amplifier gain error | $u_{gain}$ | 0.10 | Rectangular | $\sqrt{3}$ | 0.05 |
| Quantization error | $u_{quant}$ | 0.44 | Rectangular | $\sqrt{3}$ | 0.25 |
| Electric noise | $u_{noise}$ | 1.89E-10 | Rectangular | $\sqrt{3}$ | 1.09 E-10 |
| Temporal drift | $u_{temp}$ | 9.16E-10 | Rectangular | $\sqrt{3}$ | 5.29 E-10 |
| Variation of subject response | $u_{subj.resp.}$ | 8.25 | Rectangular | $\sqrt{3}$ | 4.76 |
| $u_{treshold} = [(u_{amp})^2+(u_{trunc})^2+(u_{cal})^2+(u_{gain})^2+(u_{quant})^2+(u_{noise})^2+(u_{temp})^2+(u_{subj.resp.})^2]^{½}$ | | | | | 4,77976 dB(A) |

Table 3: Hearing Protector Device Measurement Result, Combined Standard Uncertainty and Expanded Uncertainty

| | 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 |
| **St. 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 |

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

| Input Quantity | Results |
|---|---|
| SNR 84% (dB) | |
| Measured results | 22.06 |
| Combined Standard Uncertainty | 0.60 |
| Combined Uncertainty (p=95,45%) | 1.20 |
| NRRsf (dB) | |
| Measured results | 17.07 |
| Combined Standard Uncertainty | 0.6 |
| Combined Uncertainty (p=95,45%) | 1.20 |

## 9. DISCUSION D CONCLUSIONS

The methodology presented in this article reveals that the calculation of the hearing protector noise attenuation measurement 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 unimportant when compared to the subject response.

The amplitude step, quantization and calibration appear to have similar contributions to the system studied here. The results obtained from this case study, has shown that the uncertainty values are similar for all frequency bands (from 1.5 to 2.0 dB).


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