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UNCERTAINTY INVESTIGATION OF FIELD MEASUREMENTS OF AIRBORNE SOUND INSULATION

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Abstract − Sound insulation is very important for the acoustic quality of buildings. The Brazilian Association of Technical Standards, ABNT, published a set of standards concerning the evaluation of the performance of buildings up to five floors, ABNT NBR 15755, and sound insulation is one the considered topics. Minimum, intermediate and superior values are presented for some acoustic parameters.

In order to make measurements carried out by different professionals comparable with the values established in the standards, the uncertainty of the results shall be expressed. The Guide to the Expression of Uncertainty in Measurement, ISO/IEC Guide 98 (GUM), is the international document that standardizes how to assess the uncertainty of a measurement result.

In general, two types of methods are used to measure sound insulation parameters: the classical method and the new method or impulsive response method. However, there is not an established and simple procedure to obtain the measurement uncertainty. Uncertainties estimates are available only for the classical method.

Measurements of airborne sound insulation between rooms were carried out in field conditions with the impulse response method and the work presents a study of the estimate of the uncertainties of the results, in accordance with the GUM.

Keywords: measurement uncertainty, sound insulation, building acoustics

1. INTRODUCTION

A set of standards concerning the evaluation of the performance of buildings up to five floors was recently published by the Brazilian Association of Technical Standards [1]. This will lead to a demand for field measurements that has never occurred in our country. Acoustic performance is one of the topics disclosed in the standards. The sound insulation parameters shall be measured according to ISO 140 [2] and the single-number quantities for airborne sound insulation rating shall be determined according to ISO 717 [3].

The standards establish minimum, intermediate and superior values for some parameters. Such parameters will be measured by different professionals and shall be comparable with the values. Therefore, the uncertainties of those measurements must be expressed.

The uncertainty of a measurement result is defined in the international Guide to the Expression of Uncertainty in Measurement, ISO/IEC Guide 98 [4], called GUM, which standardizes how to determine and evaluate it. In this current work, the GUM was used to estimate the uncertainty of field measurements of airborne sound insulation between rooms carried out with a new method described in ISO 18233 [5].

2. AIRBORNE SOUND INSULATION

The airborne sound insulation between rooms measured in situ can be characterized by three parameters, defined in the international standard ISO 140-4 [6]. They are: apparent sound reduction index - *R’*, normalized level difference - D_n, and standardized level difference - D_{nT}, given in (1) to (3). All of them depend on the sound level difference between the source and the receiving rooms, *D*, and on room characteristics.

$$R' = D + 10\log\left(\frac{S}{A}\right) \tag{1}$$

$$D_n = D - 10\log\left(\frac{A}{A_0}\right) \tag{2}$$

$$D_{nT} = D + 10\log\left(\frac{T}{T_0}\right) \tag{3}$$

Where *S* is the area of the separating element in m^2; *A* is the equivalent sound absorption area of the receiving room (A = 0,16 V/T), according to ISO 354 [7], in m^2/Sabin; *V* is the volume of the receiving room in m^3; *T* is the reverberation time of the receiving room in s; A_0 is the reference absorption area (A_0 = 10 m^2); and T_0 is the reference reverberation time (T_0 = 0,5 s).

The sound level difference *D* can be obtained by two methods of measurement: the classical and the new methods (transfer function methods).

In the classical method, described in ISO 140-4 [6], *D* is obtained by direct measurements of the sound pressure levels in both rooms and is expressed by (4), where L_S and

L_R are the space and time average sound pressure levels in the source and receiving rooms, respectively, when the source room is being excited, obtained by the energetic average of the levels measured in different microphone positions.

$$D = L_S - L_R \tag{4}$$

In the new method, described in ISO 18233 [5, 8], D is obtained after processing the impulse response of the room or its transfer function, as expressed by (5), where H_S and H_R are the energetic space average acoustic transfer functions in the source and receiving rooms, respectively, when the source room is being excited.

$$D = H_S - H_R \tag{5}$$

The standardized level difference between rooms, D_{nT}, is one of the parameters considered in the Brazilian standards. For walls between two adjacent dwellings, the minimum acceptable values for the weighted standardized level difference, $D_{nT,w}$, range from 40 to 44 dB, the intermediate acceptable values range from 45 to 49 dB, and the superior values are equal or above 50 dB. Unfortunately, no value of uncertainty is given in the standards, but it should.

In acoustics in general, and particularly in sound insulation measurements, there is not a completely established procedure used on a broad scale to evaluate their uncertainties. Part 2 of ISO 140 [9] presents some uncertainty estimations, only for the classical technique, based on repeatability and reproducibility tests performed in some laboratories, but not based on ISO/IEC Guide 98 [4]. One should remember that in laboratories the uncertainties can be "controlled", whereas field measurements present some characteristics that can contaminate the results, as field conditions and time variance. For new techniques, there are even not repeatability and reproducibility tests to estimate the uncertainty of the results. ISO 18233 [5] states that the new methods can have "similar or better precision" relative to the classical method and that ISO/IEC Guide 98 [4] shall be used to evaluate the uncertainty of the results.

3. GUM'S UNCERTAINTY EVALUATION

The result of a measurement is an estimate of the measurand y calculated as a function of the estimates $(x_1,x_2,...,x_N)$ of the input quantities $(X_1,\ldots,X_N)$. The GUM [4] describes steps to evaluate the measurement uncertainty. The first step is to specify the measurand y and its relation with the input quantities X_i. The next step is to list the estimates x_i of the input quantities and the possible sources of uncertainty, quantifying their associated uncertainty components $u(x_i)$. Finally, the total uncertainty of the measurement result, called the combined standard uncertainty, $u_c(y)$, can be calculated by the law of propagation of uncertainty, combining all the uncertainty components. Equation (6) gives the combined standard uncertainty for uncorrelated input quantities, where c_i are the sensitivity coefficients and $u(x_i)$ are the standard uncertainties associated with x_i. The sensitivity coefficients are the partial derivatives of y with respect to x_i, $\left(c_i = \partial y / \partial x_i\right)$.

$$u_c(y) = \sqrt{\sum_{i=1}^{N} \left[c_i\right]^2 u^2(x_i)} \tag{6}$$

The interval within which the value of the measurand is believed to lie with a high level of confidence is obtained by the expanded uncertainty U of a measurement. It is the product of a coverage factor k and the combined standard uncertainty of the measurement: $U = k\, u_c(y)$. The coverage factor k is chosen based on the desired level of confidence.

The uncertainty of a measurement comprises many sources and many components and it can be quite complicated to define all these sources and components. The GUM divides the uncertainty components in two classes, A and B, depending on the method used to estimate their numerical values.

Type A estimation of uncertainty is obtained from statistical analysis of results of a series of experimental measurements, like standard deviations. The best estimate x_i of an input quantity X_i is given by the arithmetic mean $\overline{X}$ of n statistically independent observations, in repeatability conditions. The associated standard uncertainty $u(x_i)$ is given by the average experimental standard deviation, $u(x_i) = s(\overline{X})/\sqrt{n}$.

Type B evaluations are those for which there is no experimental data from a set of measurements to statistically evaluate their standard uncertainties, but there are probability distributions based on experience or other information, like calibration certificates, manufacturer's data, or the result of a previous uncertainty evaluation.

4. UNCERTAINTY ESTIMATION FOR D_{nT}

The measurand D_{nT}, expressed in (3), was chosen for the uncertainty evaluation because it is the parameter considered in the Brazilian standards. Table 1 relates the input quantities with their sensitivity coefficients and associated standard uncertainties, and Fig. 1 illustrates the cause and effect diagram, relating the parameter with its input quantities and uncertainty sources.

Table 1. Input quantities and sensitivity coefficients for the measurements of D_{nT}.

input quantities	sensitivity coefficients	standard uncertainties
$H_S\,(f)$	1	$u\,(H_S)\,(f)$
$H_R\,(f)$	-1	$u\,(H_R)\,(f)$
$T\,(f)$	$\dfrac{10 \cdot \log(e)}{T(f)}$	$u\,(T)\,(f)$

The individual uncertainty components for the input quantities were estimated from experimental measurements performed in repeatability conditions and quantified in terms of the average experimental standard deviation of the measured values. The repeatability conditions were characterized by the same in-situ situation, the same operator, and the same equipment. The resolution, also called the readability, depends on the rounding of the result and was also considered as a source of uncertainty.

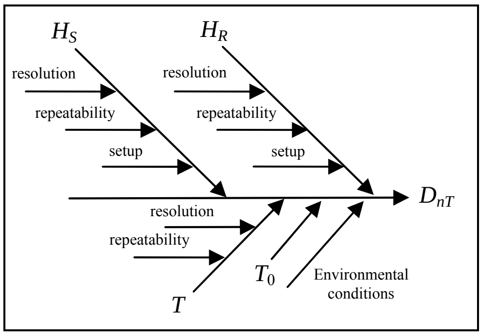

Fig. 1. Cause and effect diagrams for D_{nT}.

The uncertainty components of the transfer functions produced by the equipment setup depend on a series of contributions from: microphones, sound source, pre-amplifiers, cables, multiplexer, calibrator.

All measurements were carried out in stable environmental conditions, therefore, effects of temperature, humidity and atmospheric pressure variations were neglected in the uncertainty evaluation.

4.1. Input quantities: acoustic transfer functions H_S and H_R

The uncertainty estimates for the input quantities H_S and H_R followed the same procedure described in this section, where the subscripts $_S$ and $_R$ do not appear.

The acoustic transfer function in a frequency band can be determined by (7):

$$H(f) = H_{meas.}(f) + \delta H_{setup} + \delta H_{resolution} \quad (7)$$

Where $H_{meas.}(f)$ is the average acoustic transfer function obtained in the experimental measurements, δH_{setup} is the contribution of the uncertainty of the transfer function produced by the equipment setup and $\delta H_{resolution}$ is the contribution of the uncertainty originated from the resolution of the equipment used in the measurements.

δH_{setup} and $\delta H_{resolution}$ have null value ($\delta H_{setup} = 0$ and $\delta H_{resolution} = 0$), but their associated uncertainties $u(\delta H_{setup})$ and $u(\delta H_{resolution})$ may not be null.

The uncertainty related with the measured transfer function $H_{meas.}$ is evaluated from the average experimental standard deviation calculated for n measurements, (8). The mean value $H(f)$ calculated for n measurements is the estimated result.

$$u\left(H_{meas.}(f)\right) = \frac{s\left(H_{meas.}(f)\right)}{\sqrt{n}} \quad (8)$$

The uncertainty related with the equipment setup is calculated assuming a rectangular distribution in an interval of ± 0,5 dB, considering known contributions of the used instrumentation, as the non-flatness of the microphone and the non-linearity of the sound analyzer in the frequency range, (9):

$$u\left(\delta H_{setup}\right) = \frac{0,5}{\sqrt{3}} \quad (9)$$

The uncertainty related with the rounding of the equipment used to measure the transfer functions is calculated using the assumption of a rectangular distribution for the resolution, which is 0,1 dB. Equation (10) expresses this uncertainty source:

$$u\left(\delta H_{resolution}\right) = \frac{0,1/2}{\sqrt{3}} \quad (10)$$

Combining all the uncertainty components related to the input quantities $H_S(f)$ and $H_R(f)$, the uncertainty can be estimated, (11).

$$u\left(H(f)\right) = \sqrt{u\left(H_{meas.}(f)\right)^2 + u\left(\delta H_{setup}\right)^2 + u\left(\delta H_{resolution}\right)^2} \quad (11)$$

4.2. Input quantity: reverberation time T

The uncertainty related to the reverberation time considered the repeatability of the measurements, with the average experimental standard deviations, and the rounding of the results, expressed in (12) to (14).

$$u\left(T_{meas.}(f)\right) = \frac{s\left(T_{meas.}(f)\right)}{\sqrt{n}} \quad (12)$$

$$u\left(\delta T_{resolution}\right) = \frac{0,1/2}{\sqrt{3}} \quad (13)$$

$$u\left(T(f)\right) = \sqrt{u\left(T_{meas.}(f)\right)^2 + u\left(\delta T_{resolution}\right)^2} \quad (14)$$

4.3. Combining the uncertainty components

The law of propagation of the uncertainties, presented in (6) and rewritten in (15), was applied to obtain the final combined standard uncertainty $u_c(D_{nT})$, considering all the input quantities uncorrelated.

$$u_c(D_{nT}) = \sqrt{\left(\frac{\partial D_{nT}}{\partial H_S}\right)^2 u^2(H_S) + \left(\frac{\partial D_{nT}}{\partial H_R}\right)^2 u^2(H_R) + \left(\frac{\partial D_{nT}}{\partial T}\right)^2 u^2(T)} \quad (15)$$

5. MEASUREMENT DATA

Data used in the calculation of the uncertainties were obtained from independent measurements carried out between two adjacent rooms in a single floor building. The rooms are illustrated in Fig. 2.

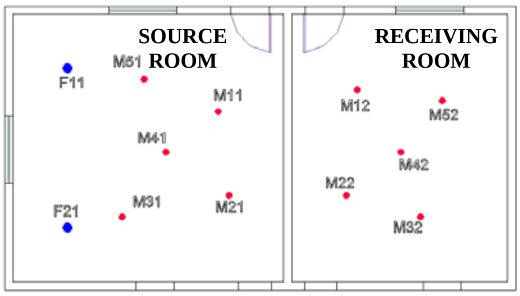

Fig. 2. Adjacent rooms.

The number and positions of microphones and source comply with the requirements in part 4 of ISO 140 [6]. The reverberation time of the receiving room was measured in accordance with ISO 354 [7].

Fig. 3 presents the mean values of the standardized level difference, obtained for third-octave bands from 100 Hz to 3150 Hz. The weighted standardized level difference, $D_{nT,w}$ is 39 dB, determined with the procedure described in ISO 717-1 [3].

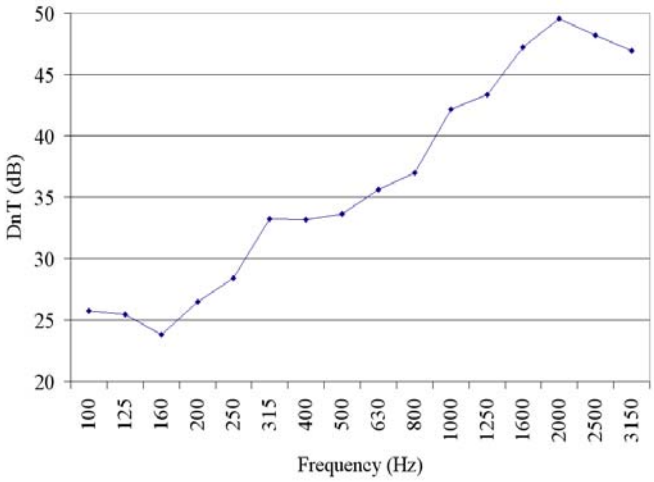

Fig. 3. D_{nT}.

6. UNCERTAINTY RESULTS

From the values of the experimental measurements, the combined standard uncertainty could be estimated and its expanded uncertainty was obtained for a level of confidence of approximately 95%, for which was calculated a coverage factor $k = 2$. Table 2 presents the results and their expanded uncertainties as functions of the frequency for D_{nT} and on the last line, for $D_{nT,w}$. The values of the expanded uncertainty are higher at low frequencies, as expected in sound insulation measurements.

Table 2. D_{nT} and its uncertainties.

Freq (Hz)	D_{nT} (dB)	**U (D_{nT}) (dB)**
100	25,7	1,2
125	25,5	1,7
160	23,8	1,2
200	26,5	1,1
250	28,4	0,9
315	33,2	1,0
400	33,2	1,0
500	33,6	1,0
630	35,6	1,0
800	370	0,9
1000	42,2	1,0
1250	43,4	1,1
1600	47,2	1,0
2000	49,6	1,1
2500	48,2	1,1
3150	47,0	1,1
$D_{nT,w}$	39,0	1,0

7. CONCLUSIONS

This work presented an initial evaluation of the standard uncertainty of the results for a set of field independent measurements of sound insulation.

The uncertainty estimation is not an easy procedure, since it is difficult to identify all sources of uncertainty related to the measurand and a methodology to evidence its metrological confidence should also be applied.

The values obtained for the uncertainty of the measurement results are lower than 2 dB. However, it should be remembered that only few sources of uncertainty and no correlation between the input quantities were considered in this evaluation.

Due to the deterministic behavior of the excitation signal, the standard deviations of the measurements performed with the new method are smaller than with the classical method, and the uncertainty with the new method is also smaller.

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