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Uncertainty evaluation in field measurements of airborne sound insulation

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The Brazilian Committee of Civil Engineering presented a set of standards concerning the evaluation of the performance of several topics for buildings up to five floors. The acoustic performance is one of them. The standards are in approval process and measurements in real buildings will be necessary. Different professionals using different equipment will emit certificates establishing which levels of insulation a certain flat provides and its uncertainties. The expanded measurement uncertainty is necessary to make different measurement results comparable.
The international Guide to the Expression of Uncertainty in Measurement, the ISO/IEC Guide 98 (GUM), is a widely accepted document to assess and evaluate the uncertainty of a measurement result, and was used in this work.
The standards concerning sound insulation measurements are ISO 140 series and ISO 18233. Uncertainty estimates are available only for the classical technique described in ISO 140, based on repeatability and reproducibility tests performed in laboratories. Field measurements present some characteristics that can contaminate the results.
Independent measurements were carried out in a single floor building using ISO 18233 specifications and the ISO/IEC Guide 98 was applied to obtain the uncertainty for measurement results of airborne sound insulation between rooms in situ.

1 Introduction

In Brazil, there is not yet an official standard establishing acceptable values for sound insulation between rooms, but a set of standards concerning the evaluation of the performance of buildings up to five floors is close to be approved [1]. Acoustic performance is one of the topics disclosed in the project of 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 project of standards establishes minimum, intermediate and satisfactory acceptable values for some parameters. Once the new standards are approved, new buildings shall comply at least with the minimum requirements.

To compare results from measurements in several buildings undertaken by different professionals with the acceptable values, the uncertainties of those measurements must be expressed, in order to compare their results.

The uncertainty of a measurement result is defined in the international Guide to the Expression of Uncertainty in Measurement, the GUM [4], as “a parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand”. The guide standardizes how to determine and evaluate the uncertainty of a measurement result.

In this current work, ISO/IEC Guide 98 [4] 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 Eqs. (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, D is obtained by the direct measurement of the sound pressure levels in both rooms and is expressed by Eq. (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. This method is described in ISO 140-4 [6] and uses a random excitation signal with continuous spectrum, as a white or pink noise, to excite the source room.

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

In the new method, D is obtained after processing the impulse response of the room or its transfer function, as expressed by Eq. (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. This method is described in ISO 18233 [5, 8] and uses a deterministic excitation signal, as the maximum length sequence or the sweep sine.

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

Because of the random excitation signal, the classical method requires time and spatial averaging in order to reduce the standard deviations, and it is normally time consuming. On the other hand, the signals used in the new methods are deterministic, so they can be accurately reproduced, improving the repeatability of the measurements.

The standardized level difference between rooms, D_{nT}, is one of the parameters considered in the Brazilian project of 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 satisfactory values are equal or above 50 dB. An uncertainty of ± 2 dB is now acceptable for field measurements of $D_{nT,w}$ between rooms.

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 ($X_1,...,X_N$). 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. Eq.(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, $\left(c_i = \partial y / \partial x_i\right)$.

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

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 $\bar{X}$ of n statistically independent observations, in repeatability conditions. The associated standard uncertainty $u(x_i)$ is given by the average experimental standard deviation, $u(x_i) = s(\bar{X})/\sqrt{n}$.

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 measured D_{nT}

The measurand D_{nT}, expressed in Eq. (3), was chosen for the uncertainty evaluation because it is the parameter considered in the Brazilian project of 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.

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

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

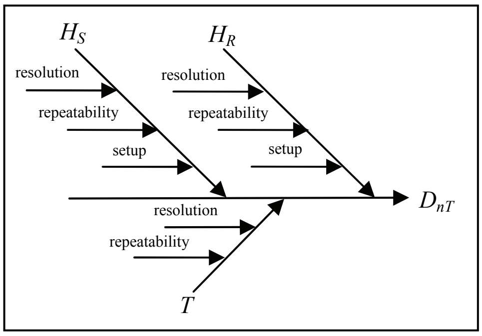

Fig. 1 Cause and effect diagrams for D_{nT}

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.

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 Eq. (7):

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

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, Eq. (8). The mean value $H(f)$ calculated for n measurements is the estimated result.

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

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, Eq.(9):

$$u\left(\delta H_{setup}\right) = \frac{0.5}{\sqrt{3}} \qquad (9)$$

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. Eq. (10) expresses this uncertainty source:

$$u\left(\delta H_{resolution}\right) = \frac{0.1/2}{\sqrt{3}} \qquad (10)$$

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

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

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 Eqs. (12) to (14).

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

$$u\left(\delta T_{resolution}\right) = \frac{0.1/2}{\sqrt{3}} \qquad (13)$$

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

4.3 Combining the components uncertainties

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

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

5 Measurement data

Data used in the calculation of the uncertainty were obtained from independent measurements carried out between two adjacent rooms in a single floor building. The source room volume is 65.8 m^3 and the receiving room volume is 51.4 m^3. The area of separating wall is 13.0 m^2. The rooms are illustrated in Fig. 2.

The number and positions of microphones and source comply with the requirements in part 4 of ISO 140 [6]. To obtain spatial averaging, five microphone positions in both rooms and two source positions in the source room were used, as shown in Fig. 2, where **M** points are the microphone positions and **F** points are the source positions. The measurements were performed with one microphone in each room, simultaneously and successively moved, with the following combinations of positions: M11-M12, M21-M22, M31-M32, M41-M42, and M51-M52, each for both source positions. The reverberation time of the receiving room was measured in accordance with ISO 354 [7].

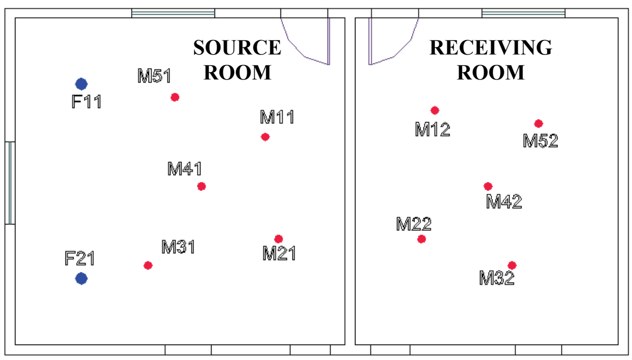

Fig. 2 Adjacent rooms

The excitation signal was a single sweep with long duration generated by the software *Monkey Forest*, driven to the amplifier and then to the sound source. The source used to excite the room was a dodecahedron loudspeaker with subwoofer. The environmental conditions kept constant during measurements and the effective signal-to-noise ratio was satisfactory in the considered frequency range.

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].

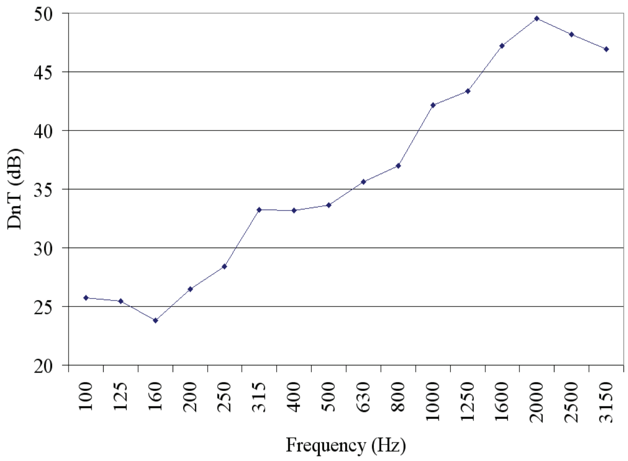

Fig. 3 D_{nT}

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}. The values of the expanded uncertainty are higher at low frequencies, as expected in sound insulation measurements.

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	37.0	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

Table 2 D_{nT} and its uncertainties

Fig. 4 shows the contributions from the uncertainty components to D_{nT} uncertainty measurement results, at the third-octave band centre frequency of 1000 Hz. Field conditions at the receiving and source room have a determinant influence on the final measurement uncertainty and the transfer functions in the source room H_S present higher standard deviations than the transfer function in the receiving room H_R.

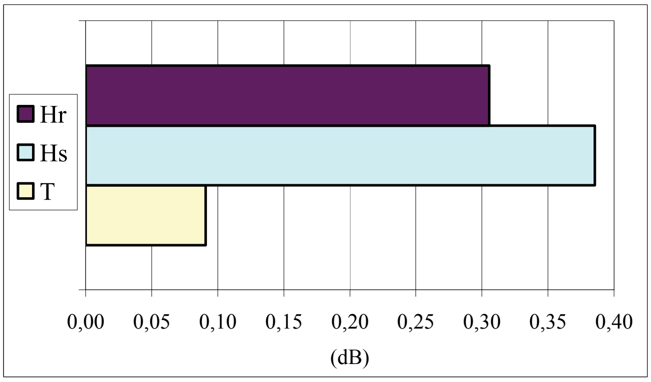

Fig. 4 Uncertainty contributions (values of $\left(\partial y/\partial x_i\right)\cdot u\left(x_i\right)$) in D_{nT} results at 1000 Hz

The measurement uncertainty budget and the uncertainty contributions are very useful and shall be carefully analysed because they allow to find important factors for the measurement results and to take necessary actions to improve the measurement procedure.

To calculate the uncertainties of the single-number quantity, $D_{nT,w}$, as described in ISO 717-1 [3], repeatability and reproducibility tests with simulation techniques, like Monte Carlo, can be applied [11].

7 Considerations

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 the Brazilian acceptable values, which is 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.

If more uncertainty sources were considered, the final combined standard uncertainty would be higher than the obtained values. Another important point is that these are results for a specific field situation condition in one specific building; therefore, more investigations need to be performed in several different conditions.

Due to the deterministic behaviour 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. Attention shall be given in order to evaluate the uncertainty and more detailed studies are necessary to better establish the estimate of uncertainties in acoustics, especially with new measurement methods.

Acknowledgments

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