UNCERTAINTY OF FAÇADE SOUND INSULATION MEASUREMENTS OBTAINED BY A ROUND ROBIN TEST: THE INFLUENCE OF THE LOW FREQUENCIES EXTENSION

Chiara Scrosati and Fabio Scamoni

ITC-CNR Construction Technologies Institute, National Research Council of Italy, Milano, Italy
e-mail: c.scrosati@itc.cnr.it

Francesco Asdrubali, Francesco D’Alessandro and Elisa Moretti

CIRIAF – University of Perugia, Perugia, Italy

Arianna Astolfi

Politenico di Torino, Energy Department, Torino, Italy

Luca Barbaresi

Department of Industrial Engineering (DIN) University of Bologna, Bologna, Italy

Gianfranco Cellai and Simone Secchi

Department of Industrial Engineering DIEF – University of Florence, Florence, Italy

Antonino Di Bella and Chiara Martina Pontarollo

Department of Industrial Engineering - University of Padova, Padova, Italy

Patrizio Fausti

University of Ferrara, Department of Engineering, Ferrara, Italy

Andrea Prato

National Institute of Metrological Research - INRIM, Torino, Italy

Corrado Schenone

Department of Mechanical Engineering (DIME) - University of Genova, Genova, Italy

Giovanni Zambon and Fabio Angelini

Department of Earth and Environmental Science, University of Milano Bicocca, Milano, Italy

The international standard ISO 140-5 for the measurement of the sound insulation of building façades will soon be replaced by the new standard ISO 16283-3. This revision includes the procedures for measurements at low frequencies down to 50 Hz. The uncertainty of façade sound insulation, in particular at low frequencies, was evaluated by a Round Robin Test, conducted in a full-scale experimental building at ITC-CNR. Each of the 10 teams involved in the RRT replicated the tests 5 times, for a total of 50 measurements. The different measurement positions inside the receiving room are compared. In particular, all the teams involved in the RRT assessed corner and center room positions; their energy average values according to ISO 16283-1 are considered and the relative uncertainty in terms of repeatability and *in situ* reproducibility standard deviations are compared with the ones measured and calculated following ISO 140-5.

1. Introduction

In recent years the attention to the measurements in the low frequency range has considerably increased. The future standard ISO 16283-3 (ISO/DIS 16283-3 [1]), that will supersede ISO 140-5 [2], includes the procedures for measurements at low frequency down to 50 Hz. The so-called low-frequency procedure shall be used for the 50 Hz, 63 Hz, and 80 Hz one-third octave bands in the receiving room when its volume is smaller than 25 m^3. Sound pressure level measurements are taken close to the corners of the room to identify the corner with the highest level in each band. This is carried out in the receiving room with the sound source in operation to determine the corner sound pressure level, and with the element or global loudspeaker method when the loudspeaker is switched off to determine the background noise level. In this paper a comparison between the standard procedure and the low-frequency procedure was made on the same façade sound insulation measurement, where the receiving room volume is 40 m^3 thus the comparison could be made.

In this study was analyzed the uncertainty of the measurement method of façade sound insulation for field measurements, with the global loudspeaker method, in terms of repeatability and *in situ* reproducibility standard deviations, by applying the statistical procedures prescribed for this kind of cooperative tests in ISO 5725 standards [3].

The measurements on which this study is based were carried out on the same building, on the same building's façade, so the airborne and structure-borne sound fields involved remain constant. Therefore, the variability in results and the standard uncertainty are related only to the measurement method itself.

2. Round Robin Test

The best way to study the repeatability and reproducibility of building acoustics field measurements [4,5] is to carry out a Round Robin Test (RRT), which consists of independent measurements executed several times by different operators.

Ten teams, coordinated by ITC-CNR - Construction Technologies Institute of the Italian National Research Council - were involved in this RRT, each of them operating with its own equipment.

The building under test is an existing experimental building located at ITC-CNR headquarters, made of prefabricated concrete panels. The building element tested was a prefabricated concrete façade with a PVC frame with double glazing 4/12/4 window. The façade is situated at the first floor. The receiving room is a rectangular room; its volume is 41 m^3 and the façade surface is 8,7 m^2.

3. One-third-octave band analysis

For each quantity under test and for each team, 21 levels were considered, corresponding to one-third-octave band from 50 to 5000 Hz.

Each team operated under repeatability and *in situ* standard deviation conditions; where the *in situ* standard deviation is a reproducibility standard deviation of the same object in the same location [6,7]. Each team followed the provisions of ISO 140-5 [2] and ISO/DIS 16283-3 [1] (low-frequency procedure), to decide the position of microphones in the receiving room and the outside loudspeaker position. In particular, the positions of the set of microphones over which averaging is carried out in one measurement were selected anew, more or less randomly, for each repeated measurement. As the receiving room volume is larger than 25 m^3, it was possible to apply both the low frequencies measurements procedure described in ISO 16283-1 [8] and the standard procedure, for a comparison of the results.

As stated in the introduction, all teams performed measurements following the global loudspeaker method, which yields the level difference of a façade in a given place relative to a position 2 m in front of the façade. All teams positioned the outside microphone 2 m in front of the façade, and the loudspeaker on the ground, with the angle of sound incidence equal to (45±5)°; some of them positioned the loudspeaker directly in front of the façade while some others in a lateral position (see Fig. 1).

Figure 1. Different loudspeaker positions: on left side in front of the façade, on right side in a lateral position. In red the measured façade.

3.1 Outliers Teams

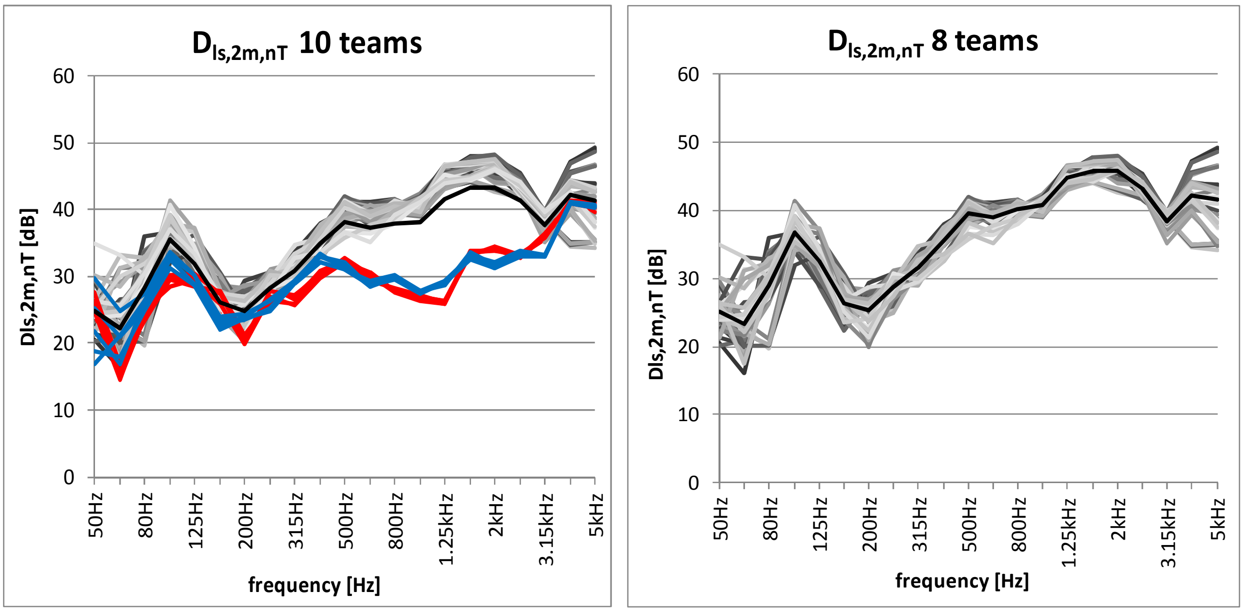

Figure 2. Standardized level difference of the façade ($D_{ls,2m,nT}$) of the 10 teams (5 repetitions for each of the 10 teams) on the left side, average (black) outlier team No 5 (blue) outlier team No 6 (red); $D_{ls,2m,nT}$ of the 8 teams (5 repetitions for each of the 8 teams) on the right side, average (black).

In the graphs of Fig. 2 are plotted the one-third octave curves, obtained following the standard measurement procedure, of the standardized level difference of façade $D_{ls,2m,nT}$, which is the level difference in decibels, corresponding to a reference value of the reverberation time in the receiving room. On the left side of the graphs of Fig. 2 are plotted the $D_{ls,2m,nT}$ of the 10 teams participating at the RRT; on the right side of Fig. 2 are plotted the $D_{ls,2m,nT}$ of the 8 teams, once the outliers teams No 5 and No 6 were excluded. The statistical analysis of the data provides a tree step procedure [3,4] for the identification of stragglers and outliers. Following this procedure, laboratories No 5 and No 6 were identified as outliers laboratories and excluded because they showed a significant presence of stragglers and outliers starting from 500 Hz to 3150 Hz. Even if it turned out that there was nothing wrong with the microphones and the measurement instrumentation, it was found that the differences between including and excluding these laboratories were remarkable. As the method was correctly followed, the presence of stragglers and outliers, without any other physical explanation, can only be attributed to an external event.

3.2 Repeatability and *in situ* standard deviation results

3.2.1 Standard measurement procedure

The repeatability (s_r) and *in situ* standard deviation (s_{situ}) obtained for the standard measurement procedure for the 8 laboratory are plotted in Fig. 3.

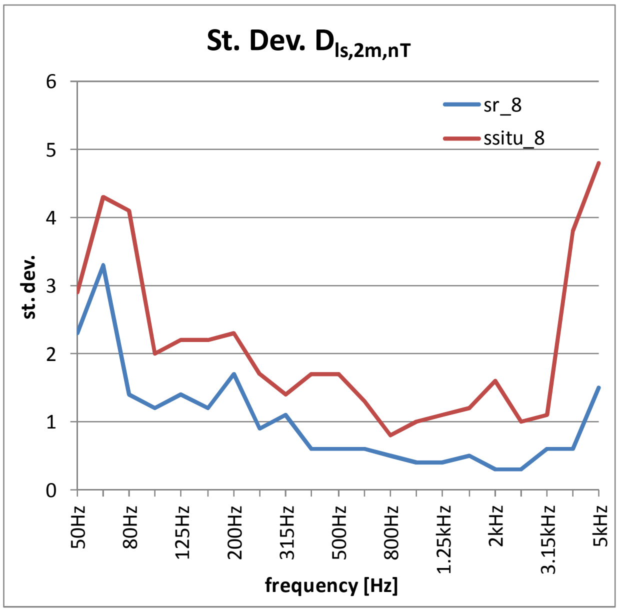

Figure 3. s_{situ} and s_r of $D_{ls,2m,nT}$ for the 8 teams.

Regarding the low frequency range (from 50 to 80 Hz) the high values of s_r and s_{situ} can be sought in the presence of the normal modes of vibration, in fact at the first three 1/3 octave bands (50, 63 and 80 Hz), the measured levels can be strongly influenced by the measurement position.

In a previous RRT on façade sound insulation [7] it was found that an important contribution to the overall uncertainty, is the uncertainty in the reverberation time measurements at low frequencies. In that case the uncertainties in $D_{ls,2m,nT}$ were heavily contaminated by the inappropriateness of the reverberation time correction at low-frequencies and a comparison between the uncertainties of the standardized level difference $D_{ls,2m,nT}$ and the level difference $D_{ls,2m}$ showed the magnitude of the reverberation time at low frequencies. In the present study no differences were found in the uncertainties behavior including or not the reverberation time correction (i.e. no differences between the $D_{ls,2m,nT}$ and the $D_{ls,2m}$ uncertainties behavior; see Fig. 4). The s_{situ} and s_r behavior of both $D_{ls,2m,nT}$ and $D_{ls,2m}$ is not similar to the behavior of the uncertainties of ISO 12999-1 [6], in terms of reproducibility s_R and *in situ* standard deviation, which increase steadily and rapidly below 100 Hz, as it can be seen in graphs of Fig. 4. This difference is not attributable to the reverberation time measurements as in the previous RRT [7].

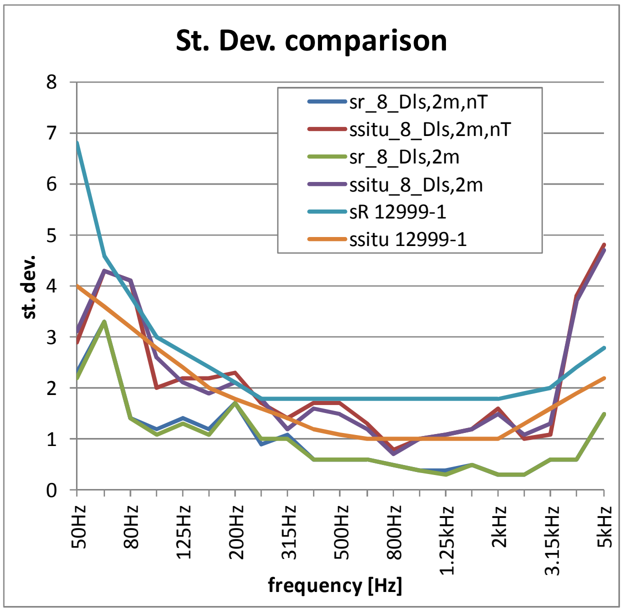

Figure 4. Comparison of standard deviation values from RRT (calculated for both $D_{ls,2m,nT}$ and $D_{ls,2m}$) and from ISO 12999-1.

Respect to the high frequency range, in particular at 4000 and 5000 Hz, the RRT and ISO 12999-1 [6] standard deviations values show the same behavior, i.e. an increase with frequency, but the RRT s_{situ} values are higher than the ISO 12999-1 values. Moreover the RRT s_{situ} values are higher than the low frequency s_{situ} values of both RRT and ISO 12999-1. This is probably due to the different positions of the loudspeaker respect to the façade (see Fig. 1) and it is still under investigation. Some studies [9,10] considered the position of the loudspeaker as a variable, but its influence on the high frequencies was not evaluated comprehensively.

3.2.2 Low-frequency procedure

The low-frequency procedure was first studied and proposed by Hopkins and Turner [11] in a work about the airborne sound insulation between rooms. For each of the 50, 63 and 80 Hz bands they proposed that the average low frequency sound pressure level in the room, L_{LF}, is calculated from $L_{ISO140-4}$ (the average sound pressure level in a room measured according to the normative guidance in ISO 140-4) and L_{corner} (the corner sound pressure level) according to:

$$L_{LF} = 10\lg\left[\frac{2\left(10^{0.1L_{ISO140-4}}\right)+10^{0.1L_{corner}}}{3}\right]\text{dB} \tag{1}$$

Referring to Hopkins and Turner [11], the weighting factor for $L_{ISO140-4}$ is empirical and has not been determined from theoretical models and any future work could look at this aspect in more detail; however this equation was adopted by ISO 16283-1 [8] and will be adopted by ISO/DIS 16283-3 [1].

In their work Hopkins and Turner evaluated also the reverberation time measurements in narrow rooms (for rooms with volumes < 50 m^3) and suggested this criterion: the product of the filter bandwidth, B, and the reverberation time, T, should be greater than eight (BT > 8). For the low frequency 50, 63 and 80 Hz if this criterion is satisfied, the reverberation time measured could be used for the calculation of R’ or D_n (or, in the case of this paper, for the calculation of $D_{ls,2m,nT}$); otherwise the 63 Hz octave band reverberation time shall be measured and this single value used to represent the 50, 63 and 80 Hz bands. The measurement of the 63Hz octave reverberation time became a part of ISO 16283-1 [8] (and will be part of ISO/DIS 16283-3[1]), in the low-frequency procedure in case of room volumes < 25 m^3.

To investigate the uncertainty in the low frequency range (50, 63 and 80 Hz), the values and the relative repeatability and *in situ* standard deviation of $D_{ls,2m,nT}$ were calculated following three different measurement procedure: the first following the standard measurement method, the second following the low-frequency procedure considering the reverberation time measured in one-third octave band (named LF) and the third following the low-frequency procedure considering the reverberation time measured in octave band at 63Hz (named LF_oct).

As illustrated in Section 3.1, the outliers laboratories could be included in the evaluation of the low frequencies uncertainties as the straggles and outliers are from 500 Hz, thus Table 1 shows the standard deviations values for the case of both 10 and 8 teams.

Table 1. Low frequency s_r and s_{situ} values for the three measurement method (standard, LF and LF_oct) for both 8 and 10 teams.

Standard deviations	50 Hz			63 Hz			80 Hz		
	standard	LF	LF_oct	standard	LF	LF_oct	standard	LF	LF_oct
s_r_10	2.7 dB	2.5 dB	2.3 dB	3.1 dB	4.5 dB	4.5 dB	1.4 dB	2.3 dB	2.3 dB
s_{situ}_10	3.1 dB	3.1 dB	3.3 dB	4.8 dB	5.5 dB	5.5 dB	4.0 dB	4.1 dB	4.1 dB
s_r_8	2.3 dB	2.3 dB	2.3 dB	3.3 dB	5.0 dB	5.0 dB	1.4 dB	2.5 dB	2.6 dB
s_{situ}_8	2.9 dB	3.2 dB	3.5 dB	4.3 dB	5.2 dB	5.2 dB	4.1 dB	4.2 dB	4.2 dB

With the low-frequency procedure there is an increase of the uncertainty, particularly noticeable at 63 Hz: the repeatability increases by about 1,5 dB while the *in situ* standard deviation increases by about 1 dB. Respect to reverberation time, at 63 and 80 Hz there are no differences considering the measurement of the 63Hz octave reverberation time or the 1/3 octave reverberation time; while some little differences are noticeable at 50 Hz.

4. Single number quantities

Two different procedures have been considered in order to determine the single number quantities (SNQs) of each team for this study. The former procedure consists in determining the SNQs according to ISO 717-1 [12] shifting the reference curve both in steps of 1 dB and 0,1 dB, toward the measured curve, until the mean unfavorable deviation is as large as possible but not more than 32 dB. The obtained SNQs are respectively $D_{ls,2m,nT,w}$ and $D_{ls,2m,nT,w,01}$.

The latter procedure consists in determining the SNQs plus spectrum adaptation terms C and C_{tr} according to ISO 717-1 [12] in the ranges provided by the standard (from 50 to 5000 Hz; from 50 to 3150 Hz; from 100 to 3150 Hz and from 100 to 5000 Hz), with one decimal place using the following equation:

$$X_{Aj} = -10\lg\sum 10^{\left(L_{ij} - X_i\right)/10} = X_w + C_j \qquad (2)$$

where: *j* is the index of spectrum No.1 to calculate C or No.2 to calculate C_{tr} according to ISO 717-1; *i* is the index of frequencies; L_{ij} are the levels indicated in ISO 717-1 at frequency *i* for spectrum *j*; X_i is the standardized level difference $D_{ls,2m,nT}$ at frequency *i* for the spectrum *j*; X_w is the SNQ; C_j is the spectrum adaptation term C or C_{tr} if calculated with spectrum No.1 or No.2, respectively. The results of SNQs calculations, for the 8 teams, are shown in Fig. 5; the relative s_r and s_{situ} are shown in Table 2 and Table 3.

Analyzing the results of Fig. 5, it can be seen that the differences between including and excluding low frequencies are very high. This is in contrast with the results of the previous RRT on façade sound insulation [7], that showed that the differences between including or not the low frequencies were practically negligible.

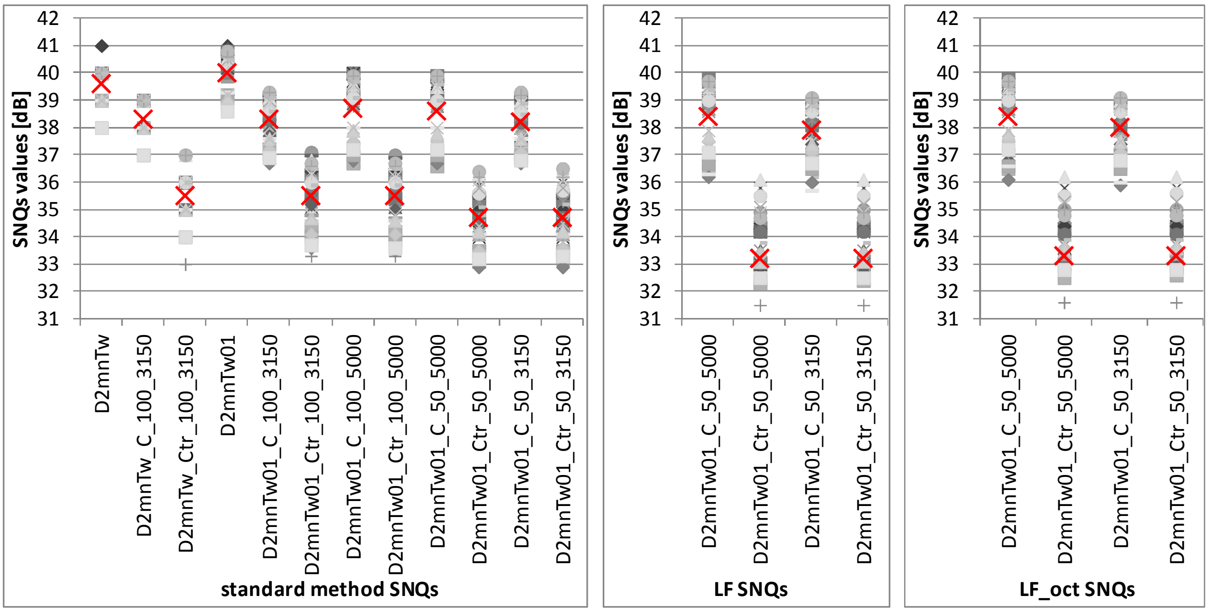

Figure 5. SNQs distribution: grey symbols are the values of the SNQs, the red crosses are the RRT mean values. Left side: standard method SNQs; center: LF SNQs; right side: LF_oct SNQs.

Table 2. Standard uncertainties of SNQs without low frequencies for the 8 teams.

Descriptor (SNQs)	s_r [dB]	s_{situ} [dB]
$D_{ls,2m,nT,w}$	0.4	0.7
$D_{ls,2m,nT,w}+C_{(100-3150)}$	0.6	0.8
$D_{ls,2m,nT,w}+C_{tr(100-3150)}$	0.8	1.0
$D_{ls,2m,nT,w01}$	0.3	0.7
$D_{ls,2m,nT,w01}+C_{(100-3150)}$	0.5	0.8
$D_{ls,2m,nT,w01}+C_{tr(100-3150)}$	0.7	1.0
$D_{ls,2m,nT,w01}+C_{(100-5000)}$	0.6	1.2
$D_{ls,2m,nT,w01}+C_{tr(100-5000)}$	0.7	1.0

Table 3. Standard uncertainties of SNQs with low frequencies for the 8 teams.

Descriptor (SNQs)	s_r [dB]			s_{situ} [dB]		
	standard	LF	LF_oct	standard	LF	LF_oct
$D_{ls,2m,nT,w01}+C_{(50-5000)}$	0.6	0.6	0.6	1.2	1.3	1,2
$D_{ls,2m,nT,w01}+C_{tr(50-5000)}$	0.8	1.9	1.8	1.0	2.1	2,0
$D_{ls,2m,nT,w01}+C_{(50-3150)}$	0.5	0.6	0.6	0.8	1.0	1,0
$D_{ls,2m,nT,w01}+C_{tr(50-3150)}$	0.8	1.9	1.8	1.0	2.1	2,0

From the experience derived from many measurements of façade sound insulation [13,14], the lower the insulation of a window, the lower the spectrum adaptation term C_{tr}. On the other hand, the higher the window insulation, the higher C_{tr}. For this reason, in the case of the previous RRT [7] the difference between $D_{ls,2m,nT,w}$ and $D_{ls,2m,nT,traffic}$ (SNQs proposed by Sholl et al. [15] that correspond to $D_{ls,2m,nT,w}$ + $C_{tr,50\text{-}5000}$) averages, was not high, only 1.5 dB, while in the case of the present study, the difference between the average values of $D_{ls,2m,nT,w}$ and of $D_{ls,2m,nT,w}$ + $C_{tr,50\text{-}5000}$ is 5.3 dB for standard measurements and 6.8 dB for low-frequency method; and the difference between the $D_{ls,2m,nT,w}$ and of $D_{ls,2m,nT,w}$ + $C_{tr,100\text{-}5000}$ averages is 4.5 dB for both standard and low-frequency method. It is interesting to note that the average values did not change significantly whether including or not the high frequencies. The uncertainty in case of low-frequency method increases very much (twice for LF_oct and more than double for LF). Although at 4000 and 5000 Hz the uncertainty is very high, this does not influence the uncertainty of the SNQs (see the comparison between SNQs with spectrum adaptation term from 100 to 3150 and from 100 to 5000, in Table 2).

5. Conclusions

In this paper a comparison between the standard procedure and the low-frequency procedure was made on the same façade sound insulation measurement. It was found that the low-frequency procedure yields to lower SNQs values, when the low frequencies are included. Moreover the uncertainty of SNQs measured with low-frequency method are higher than the ones measured with standard method. With the low-frequency procedure there is an increase of the uncertainty, which is particularly noticeable at 63 Hz. Respect to reverberation time, at 63 and 80 Hz there are no differences considering the measurement of the 63Hz octave reverberation time and using this single value to represent the 50, 63 and 80 Hz bands or the 1/3 octave reverberation time; while some little differences are noticeable at 50 Hz. At 4000 and 5000 Hz very high uncertainties, that not influence the SNQs and that need a deeper investigation, were found.

REFERENCES

1 ISO/DIS 16283-3:2014 Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 3: façade sound insulation.

2 ISO 140-5:1998 Acoustics - Measurement of sound insulation in buildings and of building elements - Part 5: Field measurements of airborne sound insulation of façade elements and façades.

3 ISO 5725 part 1 and 2:1994 Accuracy (trueness and precision) of measurement methods and results - Part 1: General principles and definitions and Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method.

4 Scrosati C., Scamoni F., Bassanino M., Mussin M. and Zambon G. Uncertainty analysis by a Round Robin Test of field measurements of sound insulation in buildings: Single numbers and low frequency bands evaluation - Airborne sound insulation. *Noise Control Engineering Journal* **61**(3) 291-306 (2013).

5 Scrosati C. Scamoni F. Measurement uncertainty in building acoustics, *Proceedings of the 22^nd^ International Congress on Sound and Vibration*, Florence, Italy, 12–16 July, (2015).

6 ISO 12999-1:2014 Acoustics - Determination and application of measurement uncertainties in building acoustics - Part 1: Sound insulation

7 Scrosati C., Scamoni F. and Zambon G. Uncertainty of Façade Sound Insulation in Buildings by a Round Robin Test. *Applied Acoustics* **96**, 27-38, (2015).

8 ISO 16283-1:2011 Acoustics - Field measurement of sound insulation in buildings and of building elements — Part 1: Airborne sound insulation.

9 Berardi U., Cirillo E. And Martellotta F., Interference effects in field measurements of airborne sound insulation of building façades, *Noise Control Engr. J.,* **59**(2), 165–176, (2011).

10 Berardi U., The position of the instruments for the sound insulation measurement of building façades: From ISO 140-5 to ISO 16283-3, *Noise Control Engr. J.* **61**(1), 70-80 (2013).

11 Hopkins C. and Turner P., Field measurement of airborne sound insulation between rooms with non diffuse sound fields at low frequencies, *Applied Acoustics*, **66**(12), 1339–1382,(2005).

12 ISO 717-1:2013 Acoustics - Rating of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation.

13 Masovic D., Miskinis K., Oguc M., Scamoni F., and Scrosati C., Analysis of façade sound insulation field measurements – Influence of acoustic and non-acoustic parameters, *Proceedings of INTER-NOISE 2013*, Innsbruck, Austria 15-18 September (2013).

14 Masovic D., Miskinis K., Oguc M., Scamoni F., and Scrosati C., Analysis of façade sound insulation field measurements – Comparison of different performance descriptors and influence of low frequencies extension, *Proceedings of INTER-NOISE 2013*, Innsbruck, Austria 15-18 September (2013).

15 Scholl W., Lang J. and Wittstock V., Rating of sound insulation at present and in future. The revision of ISO 717, *Acta Acustica united with Acustica*, 97, 686–698, (2011).