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MEASUREMENT UNCERTAINTIES FOR AIRBORNE AND IMPACT SOUND INSULATION BUILDING ACOUSTIC PARAMETERS FROM INTERLABORATORY COMPARISON

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ABSTRACT

This paper represents the results of the interlaboratory comparisons (ILC) conducted in the purpose to test proficiency of accredited laboratories (23) according to in-situ measurement methods described in ISO 16283-1:2014/A1:2017, ISO 16283-2:2020 with ISO 717-1:2020 and ISO 717-2:2020. The comparison of all measurement parameters and single number building acoustic parameters are presented with obtained measurement uncertainties. The overall influence of all uncertainty components on the results are analyzed and discussed. The measurement uncertainties are obtained by doing one independent measurement from each lab and they are determined at the end for all results in reproducibility conditions. The obtained values for standard deviations are compared with values given in standard ISO 12999-1:2020 and with previous ILC-s results for airborne and impact sound insulation parameters.

Keywords: *interlaboratory comparison, airborne and impact building acoustic parameters, one independent measurement, repeatability, and reproducibility conditions.*

1. INTRODUCTION

The Croatian Acoustical Society organized an interlaboratory comparison scheme in the field of sound insulation measurements in building acoustics. Quality control is the main motivation for individual laboratories to participate in the ILC, or usage of obtained uncertainties for measured parameters in their reports. All participants certify the sound insulation performance of different building elements for external customers [1]. Each of the 23 applied labs that submitted results performed one independent measurement (5 or 6 sound pressure level measurements for both fixed and rotation microphone positions per one source position according to ISO 16283-1:2014 (A1:2018) and ISO 16283-2:2020 standards [2, 3].

In the ILC, the heavyweight partition made of 25 mm block with 5 cm plaster from both sides on the wall between two rooms is considered for the airborne sound insulation measurements. The heavyweight floating floor is considered for the impact sound insulation measurements. The receiving room was the same for airborne and impact sound insulation measurements. In this ILC-s, not only acoustic insulation parameters are compared, but also all other measured parameters, like the geometrical parameters of rooms (volumes without furniture and area of the considered partition) and reverberation times T in one-third octave bands in the receiving room [4].

In this report, statistics of all measured acoustic and geometrical parameters and their connection with the guide for uncertainty in measurements (GUM) have been done [5] having purpose to evaluate the measurement uncertainties u(X). This is usually obtained by repeating the measurements under similar conditions and analyzing the

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Corresponding author: antonio.petosic@fer.hr results using statistical tools to estimate the dispersion of the results.

In this report, the measurement uncertainty for each lab-reported parameter is calculated from standard deviations in repeatability conditions obtained considering the experimental measurement uncertainty of all input parameters according to Annex C in ISO 12999-1:2020 [6]. Additional calculations are done for all input parameters by the organizer with the purpose of comparing the measurement uncertainty of each measured parameter from which the assessed building insulation parameter is calculated, assuming full correlation between parameters.

The determination of the standard deviations in the repeatability (s_r) and reproducibility conditions (s_R) of a test method obtained by an interlaboratory comparison, considering the procedures given in international standards [5,6] The values for s_r and s_R are given in ISO 12999:1-2020 [6] for situation B which is considered in this ILC. The obtained measurement uncertainties for relevant parameters (R' and L'_n) in each one-third octave band and for single number values is compared with obtained values given in ISO 12999-1:2020 [6].

2. THEORETICAL BACKGROUND

2.1 Airborne sound insulation parameters

There are two standardized parameters used for the expression of the airborne sound insulation: the standardized level difference D_{nT} between rooms or the apparent sound reduction index R' of the separating element as a function of frequency in one-third octave bands, whichever is appropriate. Each lab in this ILC determined all parameters, but the sound reduction index has been considered in more detail regarding the assessment of limit values in Croatia and Slovenia. The sound reduction index R' depends on the area of the measured element (S) and on the equivalent absorption area (A), which is calculated from geometrical dimensions (volume of the receiving room) and measured reverberation time in the receiving room. The sound reduction index is given by Eqn. (1) where D is level difference for each source position [3]:

$$R' = D + 10 \cdot log_{10}(\frac{S}{A}) \tag{1}$$

The A of the receiving room is given by Eqn. (2) and it is calculated in one-third octave bands due to reverberation time T:

$$A = 0{,}161 \; \frac{V}{T} \tag{2}$$

where V is the receiving room volume (m^3) with the furniture excluded [4].

2.2 Impact sound insulation parameters

The impact sound insulation can be expressed with two parameters: the normalized impact sound pressure level (L'_n) and the standardized impact sound pressure level (L'_{nT}) as a function of frequency in one-third octave bands. Normalized impact sound pressure level (L'_n), given with Eqn. (3), is the impact sound pressure level in the receiving room L'_i (averaged in time and space) increased by a correction term due to absorption surface, which is given in dB and is ten times the common logarithm of the ratio of the measured A of the receiving room (given with Eqn. (3)) to the reference absorption area $A_0 = 10\ m^2$.

$$L'_n = L_i + 10 \cdot log \frac{A}{A_0} \tag{3}$$

The problem with single-number values for sound insulation parameters and their uncertainties can be determined according to ISO 717-1:2020 [7] and ISO 717-2:2020 [8]. There is a big problem in finding correlation coefficients for different types of testing objects (separating walls in different rooms) between one-third octave bands in the interest frequency range (50 Hz–5000 Hz) for the determination of weighted sound insulation parameter uncertainties [9]. Also, the correlation parameters between some parameters (levels and reverberation time) must be found to obtain correct measurement uncertainty values.

In this work, the results of 23 laboratories (which submitted measurement results) are presented with their individual measurement uncertainty determined as standard deviations in repeatability conditions. Also, overall measurement uncertainty from all measurement results without outliers has been determined.

2.3 Measurement uncertainty due to energetic averaging of levels

Statistical analysis has been done for all measured parameters to see their experimental measurement uncertainty and influence on the measurement uncertainty determined from each individual independent measurement for each laboratory.

The Eqn. (4) for experimental standard deviation in repeatability conditions is valid if the difference between measured values (expressed in dB) is small.

$$\sigma = s(x_i) = \sqrt{\frac{1}{N-1} \cdot \sum_{k=1}^{n} (x_i - \bar{X})^2} \tag{4}$$

In the general case, the more correct equation is given by using Eqn. (5) when measured quantities are converted to relative numbers, and vice versa [10]:

$$u(x_i) = 10 \cdot log_{10}\left(10^{0,1 \cdot L_k} + S(x_i)\right) - L_k \tag{5}$$

where L_k is the energetically averaged sound pressure level of N_m measurements according to eq. (6) [10]. The eq. 9 should be used in finding standard deviations when sound pressure levels are pronounced to change especially at lower frequencies under the influence of standing waves.

$$L_k = 10 \cdot log_{10}\left(\frac{1}{N_m} \cdot \sum_{i=1}^{N_m} 10^{0.1 \cdot L_i}\right) \tag{6}$$

This equation is valid only if each of the independent measurements has the same duration. Otherwise, an additional time weighting should be used when calculating the averaged value. $S(x_i)$ is obtained with Eqn. (7),

$$S(x_i) = \sqrt{\frac{1}{n-1} \cdot \sum_{k=1}^{n} \left(10^{\frac{L_i}{10}} - 10^{\frac{L_k}{10}}\right)^2} \tag{7}$$

$u(x_i)$ is the standard measurement uncertainty for measurand connected with sound pressure levels in db. The overall measurement uncertainty is given in the case where there is no correlation between parameters with Eqn. (8) together with all other measurands included in equations for parameters.

$$u = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 \cdot u^2(x_i)} \tag{8}$$

If the measured variables are correlated, then the equation becomes a bit more complicated and is given with Eqn. (9) [9].

$$u = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 \cdot u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \cdot \frac{\partial f}{\partial x_j} \cdot u(x_i, x_j)} \tag{9}$$

There is a big problem in finding the correlation coefficient between variables $r(x_i, x_j)$ [9,11]

The measurement uncertainty from one individual measurement of each parameter is rather complicated because it includes all parameters and their functional dependence.

2.4 Experimental measurement uncertainty for determined building acoustic parameters

For standardized level difference (D_{nT}), the derivation of the measurement uncertainty by knowing the measurement uncertainties and sensitivity coefficients of all parameters that enter in the equation for calculation is given in [11], and here the equation for *R*' experimental measurement uncertainty is derived and given in Eqn. (10).

$$u(R') = \sqrt{\begin{gathered}(c_{L1} \cdot u(L_1)^2 + \left(c_{L2} \cdot u(L_2)\right)^2 + (c_{Lres} \cdot u(L_{res})^2 + \\ \left(c_S \cdot u(S)\right)^2 + \left(c_V \cdot u(V)\right)^2 + (c_{inst} \cdot u(L_{inst})^2\end{gathered}} \tag{10}$$

Where L_1 and L_2 are energetically averaged sound pressure levels in the source and receiving room, L_{res} is residual noise level in receiving room, V is volume of receiving room without furniture and L_{inst} is experimental measurement uncertainty for instrument (0,5 dB for Class1) and c are sensitivity coefficients for each input parameter. The levels in the receiving room are corrected due to the influence of background noise for each source position as suggested in standards ISO 16283-1,2. The correction formula for the sound pressure levels in the receiving room due to residual noise is derived in [9].

The equations for sound reduction index (*R'*) and estimated measurement uncertainties when measurements are done for two loudspeaker positions and calculation of sound reduction index are done for each loudspeaker position (R'_1 and R'_2) is shown in Eqn. (11):

The averaged value of airborne sound insulation for measurement results for two loudspeaker positions is given with Eqn. (12):

$$R' = -10 \cdot \log\left(\frac{1}{2} \cdot \left(10^{\frac{R_1}{10}} + 10^{\frac{R_2}{10}}\right)\right) \tag{11}$$

The measurement uncertainty $u(R')$ from known measurement uncertainties from results for two different loudspeaker positions is given by using Eqn. (12).

$$u(R') = \sqrt{(c_{R1} \cdot u(R_1)^2 + \left(c_{R2} \cdot u(R_2)\right)^2} \tag{12}$$

This calculation for each individual source position is repeated also for all sound insulation parameters in ISO 16283-2:2020 according to Eqn. 13 and 14.

The normalized impact sound pressure level L'_n has been found from individual results per source position according to Eqn. (13).

$$L'_n = 10 \cdot log_{10}(\frac{1}{N} \cdot \left(10^{\frac{L'_{n1}}{10}} + 10^{\frac{L'_{n2}}{10}} + 10^{\frac{L'_{ni}}{10}} + \cdots \ldots 10^{\frac{L'_{n,N}}{10}}\right) \quad (13)$$

by considering parameters for each individual position and measurement uncertainty for normalized impact sound pressure level has been found according to Eqn. (14).

$$u(L'_n) = \sqrt{\begin{matrix}(c_1 \cdot u(L'_{n1})^2 + (c_2 \cdot u(L'_{n2})^2 + \cdots \\ +(c_i \cdot u(L'_{ni})^2 + \cdots (c_N \cdot u(L'_{nN})^2\end{matrix}} \quad (14)$$

The experimental measurement uncertainty for each measurement position has been found by using full correlation assumption between input parameters for expressing L'_{n} according to Eqn. 15.

$$(L'_{ni}) = \sqrt{(c_{Li} \cdot u(L_i)^2 + (c_{Lres} \cdot u(L_{res})^2 + (c_T \cdot u(T)^2 + (c_V \cdot u(V))^2 + \cdots (c_{inst} \cdot u(L_{inst}))^2}$$

(15)

The main problem is to find uncertainty for sound pressure when continuous moving microphone is used because there is only one measurement result for levels at one source (loudspeaker or tapping machine) position.

In this ILC the majority of participant have used 5 or more fixed microphone positions per source position or minimum 2 or more rotations per each source position (minimum 2 sound sources positions for airborne sound insulation measurements and minimum 4 tapping machine positions for impact sound insulation measurements).

2.5 Detecting outliers

The results of all labs are averaged, and the mean value is checked with Grubb's statistics and standard deviations (from individual measurements) are checked with Cochran's statistics [5].

An outlier can be considered as a result which is sufficiently different from all other results to warrant further investigation. When carrying out the outlier tests, the outliers should not be discarded or rejected purely from a statistical point of view. For each sample the reason why, the result is different from all the others should be investigated and identified. For each laboratory or level of interest or sample, most outlier tests compare some measure of the relative distance of a suspect result to the mean of all results and assess this comparison to ascertain if the result could have occurred by chance.

3. MEASUREMENT RESULTS

3.1 Geometrical parameters

The measure geometrical parameters with standard deviation are shown in Figure 1. (no lab reported standard deviations, there were no outliers).

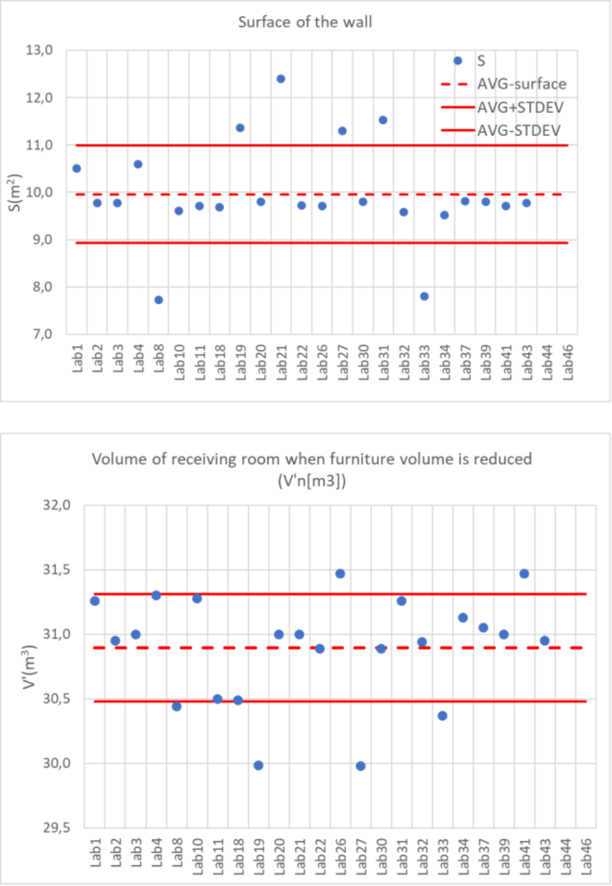


Figure 1. Measured surface of the wall and volume of the receiving room without furniture.

The experimental measurement uncertainty for the surface of the wall is u(*S*)=0.22 m^2 and for volume of the receiving room without furniture was u(*V*)=0.01 m^3. This data are used in calculation of experimental measurement uncertainty of main building acoustic parameters.

3.2 Reverberation Time

The reverberation time (mean value) and experimental measurement uncertainty for each lab obtained in one independent measurement are shown in Figure 2. (removed outliers according Cohran and Grubbs) test.

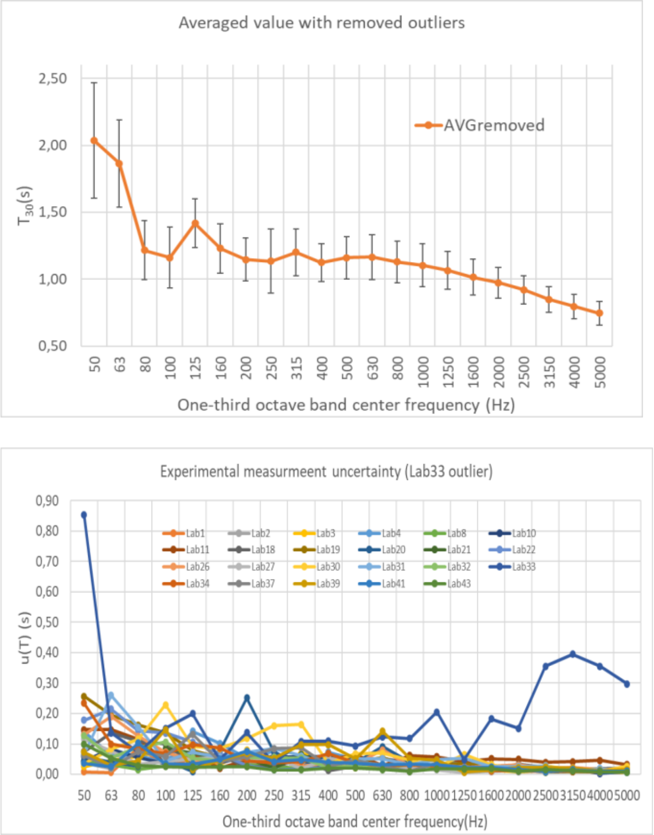


Figure 2. Reverberation time with standard deviations and experimental measurement uncertainty for each lab in one-third octave band.

There were a problems (Lab 33) with using pistol of large calibers in small room due to excitation of window glass to vibrate and problems with sound level meters to get dynamic range at some frequencies (even residual noise was very low-below 25 dB in each one-third octave band). The experimental measurement uncertainties were used in further calculations of R' with sensitivity coefficients.

3.3 Airborne sound insulation parameters

3.3.1 Level difference and residual noise

The level difference with standard deviations (overall results) for all laboratories in one-third octave bands is shown in Figure 3.

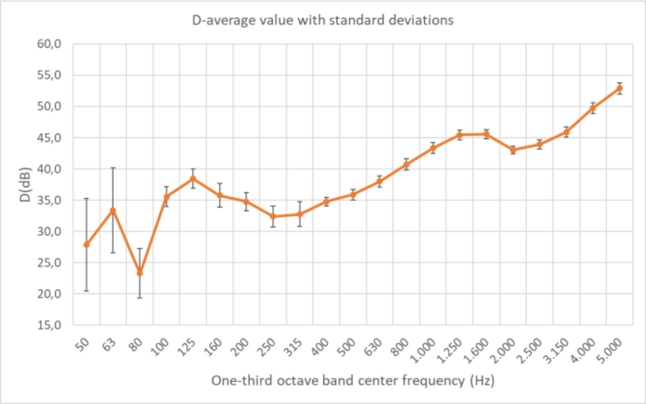
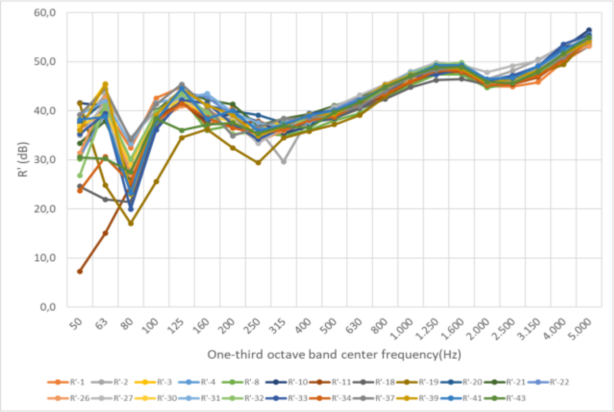


Figure 3. Level difference *D* for each individual lab (averaged for two positions) and averaged value with standard deviations.

Lab 11 has used A-frequency weighting for SPL so the level difference at lower frequencies is much lower than other labs due to influence of residual noise. Lab 19 misused the provided table with all data and calculations, so the level difference was lower in mid frequencies together with single number values.

3.3.2 Sound reduction index

The sound reduction index in one-third octave bands is shown in Figure 4.



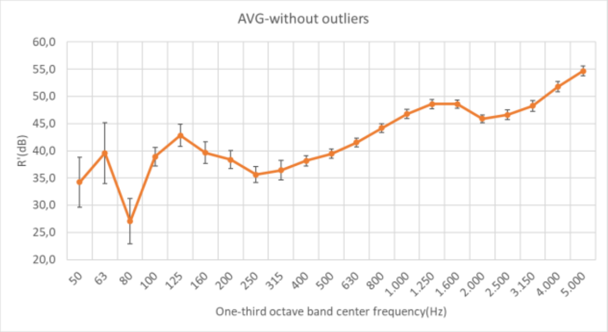


Figure 4. Sound reduction index in one third octave bands for each individual lab and averaged value with standard deviations (overall results).

3.3.3 Single number value for R'_w index with spectral adaptation terms

The results for single number value R'_w after rounding corrections are shown in Figure 5 with the probability density function PDF.

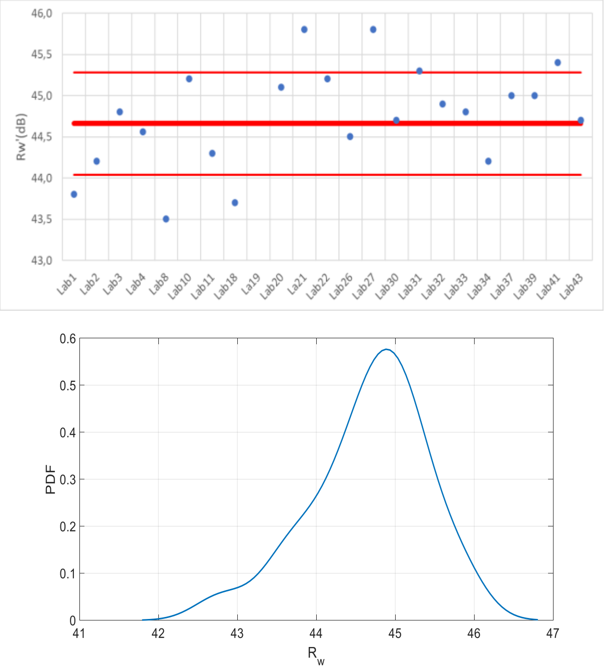


Figure 5. Single number value for R'_w with PDF function (22 results).

3.3.4 Experimental measurement uncertainties

The experimental measurement uncertainty for parameter *R*', u(*R'*) is calculated in each one-third octave bands from each individual measurement according to Eqn. 10 is shown in Figure 6 compared with previous ILC-2015 and values from ISO 12999-1:2020 standard.

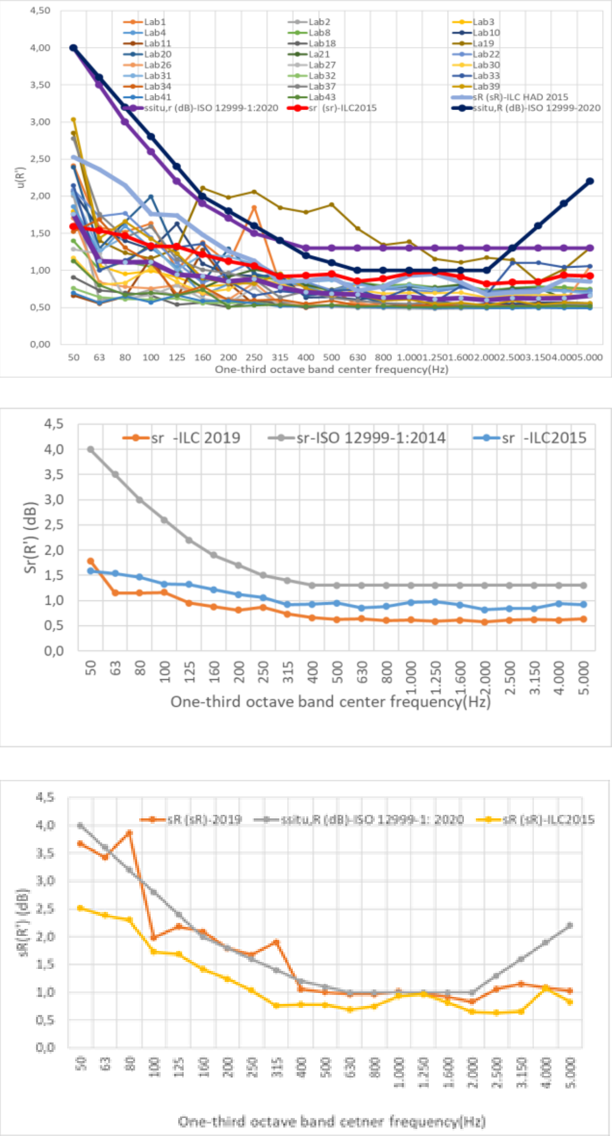


Figure 6. Calculated experimental measurement uncertainties u(R') and values from ISO 12999-

1:2020 and previous ILC2015 (5 independent measurements with full correlation assumption).

It is visible that s_R are approximately same as from the standard (except some peaks at resonance frequencies of frequencies of a room). If we observe all results from a statistical point of view the measurement uncertainty is given in Table 1. It is calculated from all reported results with excluded outliers.

3.4 Impact sound insulation parameters

The impact sound pressure levels per each tapping machine position are analyzed and for the first position is shown in Figure 7. It is evident that Lab 11 used A-weighting.

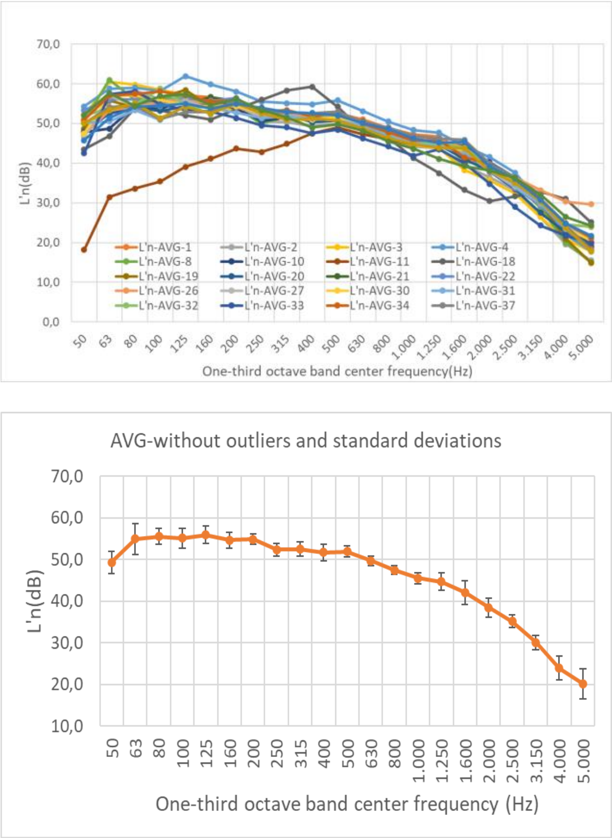


Figure 7. L_i for first measurement position and L'_n parameter in each one-third octave band together with averaged value with standard deviations.

3.4.1 Measurement uncertaitnies for L'_n

Measurement uncertainties $u(L'_{n,w})$ in each one-third octave band and compared with values from previous ILC and ISO 12999-1:0220 standard. The results for each individual lab compared with standard deviations in repeatability s_r and reproducibility conditions s_R are shown in Figure 8[12].

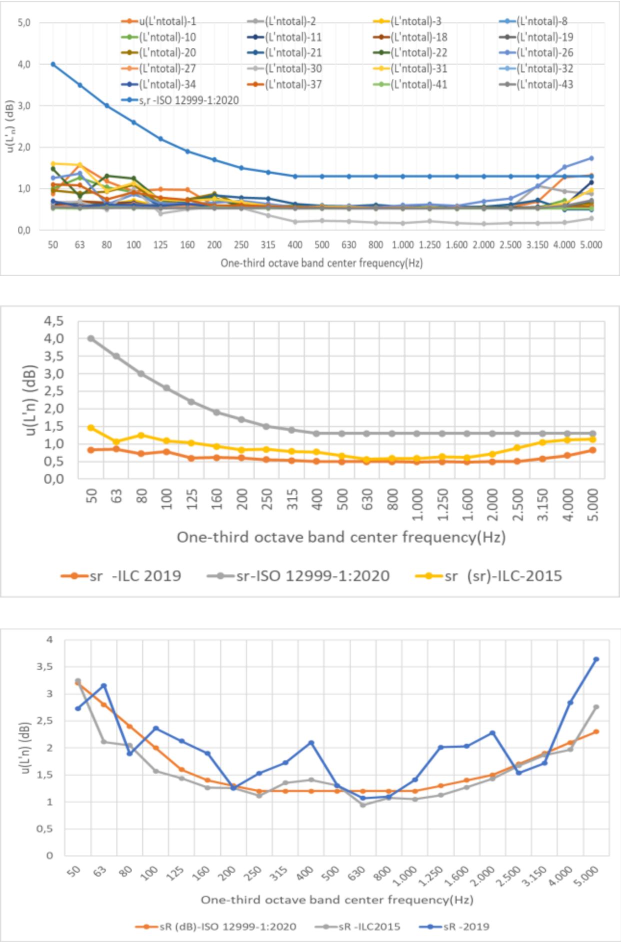


Figure 8. Experimental measurement uncertainties in each octave band from individual measurement and comparison between values for s_r and s_R from previous ILC and standard ISO 12999-1:2020.

4. CONCLUSION

It is evident that experimental measurement uncertainty in one-third octave bands in repeatability conditions is significantly lower than compared to the values from standard but the procedure for calculation is complex for accredited labs.

Some labs used A-weighting spectrum for all parameters which have influence on their results. Some labs partially entered their results in provided excel tables given from organizer (they didn't shift the reference curves and calculated spectral adaptation terms). This had to be done by the organizer having the purpose to compare all results.

In the single number value calculation, the labs haven't checked shifting the reference curve on instrument or software together with spectral adaptation terms calculations. The spectral adaptation terms should be calculated correctly by appropriate rounding of single-number values (upper value means ROUNDUPP ($L'_{n,w}$=56,1 dB is $L'_{n,w}$=57 dB) and X_A is rounded normally as explained in ISO 717-2:2020 Standard.

It is recommended to use experimental uncertainties from each individual measurement to find u(R') and u(L'_n) and to obtain the right value of expanded measurement uncertainty for single-number parameter because the values for single number uncertainties even assuming full correlation are lower compared when using values from standard obtained by averaging the results from many ILC.

It is observed when suspicious results are removed that probability density function of the results for R'_w and L'_n can be approximated by Gauss distribution (t-Student for lower number of samples). In distribution curve for $L'_{n,w}$ it is visible asymmetric behavior around central value. Normalizing and averaging those types of curves can be used to calculate probability interval that some value is in the proposed range.

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