European round robin test for the improvement of impact sound insulation of a vinyl floor covering

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Abstract
The improvement of impact sound insulation of floor coverings can be measured in the laboratory according to the standard ISO 10140. At present, ISO 12999-1 gives standard uncertainties for the reduction of impact noise by floor coverings at reproducibility conditions only. To evaluate both the repeatability and reproducibility of the test method, a round robin test was set up by the WG Acoustics of ENBRI (European Network of Building Research Institutes). Each of the 9 laboratories involved received 3 samples cut from the same vinyl floor covering and performed 4 tests. The reproducibility standard deviations of the round robin test agree well with the ISO 12999-1 values at low frequencies, but are significantly larger from 500 Hz upwards. The influence of sample variability seems to be negligible. In most frequency bands, the repeatability standard deviation is lower than the ISO 12999-1 standard uncertainty for impact sound insulation at repeatability conditions.

Keywords: building acoustics**,** laboratory tests, uncertainty, repeatability, reproducibility

1 Introduction

When measuring the airborne or impact sound insulation according to ISO 10140, the results may vary between different laboratories. At low frequencies, the variability is mainly caused by the non-diffusiveness of the sound fields in the rooms and the vibration fields in the structures [1]. At higher frequencies, the uncertainty is mainly related to limitations of the laboratory (e.g. flanking transmission, background noise) or differences in construction details (e.g. boundary conditions which influence loss factors) [2,3]. To limit the uncertainties as much as possible, the standards ISO 10140-1 [4] and ISO 10140-5 [5] set requirements for test facilities and application rules for specific products.
The standard ISO 12999-1 [6] assesses uncertainties for building acoustical measurements. Because a lot of factors influence the uncertainty in sound insulation measurements, it is very difficult to determine a detailed uncertainty budget following GUM (ISO/IEC Guide 98-3 to the expression of uncertainty in measurement). Instead, the standard uses the traditional concept of reproducibility and repeatability, which enables the uncertainty to be estimated from inter-laboratory tests [7].
Most inter-laboratory studies in the past concerned airborne sound insulation, while round robin tests on impact sound insulation are limited. As a result, no results are currently available in ISO 12999-1 for impact sound insulation at reproducibility conditions and for the reduction of impact noise at repeatability conditions. An inter-laboratory test for the improvement of impact sound insulation of a vinyl floor covering was thus set up by the WG Acoustics of the European Network of Building Research Institutes (ENBRI) [8]. The goal of the round robin test was (1) to improve the quality of measurement results of ENBRI institutes,

(2) to obtain data on repeatability and reproducibility as input for ISO 12999-1 and (3) to gain insight in the influence of some parameters on the uncertainty values.

2 Materials and methods

2.1 Participating laboratories

A total of 9 laboratories took part in this round robin test (RRT). All laboratories are (appointed by a) member of ENBRI, the European Network of Building Research Institutes. The participating laboratories are located in Belgium, Denmark, Finland, Norway, Poland, Portugal, Romania, Sweden and Switzerland.
The main characteristics of each laboratory are given in Table 1 (room volume V, floor dimensions $L \times W$, floor area S, bare floor thickness t). The laboratories are numbered in a random way to keep the data anonymous. All laboratories meet the requirements from ISO 10140-5 [5] regarding the minimum volume of the receiving room (50 m³), the minimum length of the shortest edge of the test opening (2.3 m), the surface of the test opening (10 – 20 m²) and the thickness of the reinforced concrete base floor (100 – 160 mm), except laboratory 7 for which the surface area of the floor is smaller than 10 m². Nevertheless, the measurement results of laboratory 7 have not been discarded in the statistical analysis.

Table 1 –Main characteristics of the participating laboratories.

Lab.	Room	Heavyweight reference floor			Tapping machine	Microphones	
	V [m³]	$L \times W$ [m×m]	S [m²]	t [mm]	# positions	type	# positions
1	138	4.00 x 3.00	12.0	150	9	rotating	1
2	67	4.43 x 2.60	11.5	140	6	rotating	2
3	56	3.90 x 3.05	11.9	160	5	rotating	1
4	64	4.35 x 2.65	11.5	140	5	rotating	1
5	200	3.70 x 2.80	10.4	140	5	rotating	1
6	145	4.00 x 3.00	12.0	100	4	fixed	4
7	119	3.42 x 2.42	8.3	140	6	fixed	6
8	51	5.04 x 3.74	18.8	160	6	rotating	1
9	243	3.37 x 2.99	10.2	140	6	rotating	1

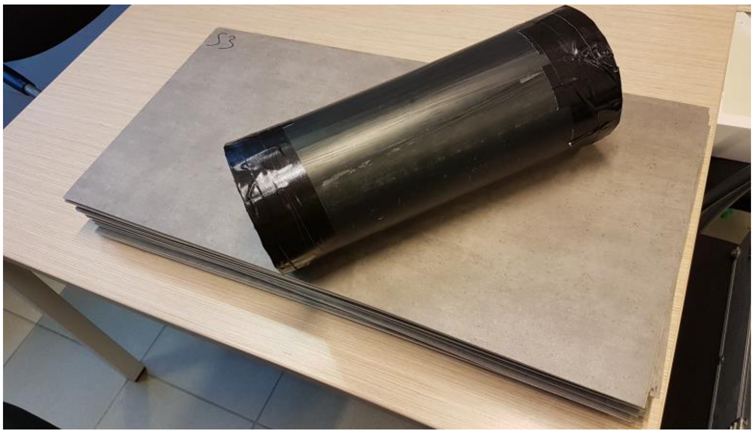


Figure 1 – Vinyl floor covering test samples sent to the participating laboratories.

2.2 Test samples

A 3 mm thick vinyl floor covering with resilient backing was chosen as test specimen. All participants of the RRT received three nominally identical test specimens (labelled s1, s2 and s3) cut from the same vinyl floor covering with dimensions 7 m x 4 m. The test specimens with approximate dimensions 800 mm x 400 mm were sent in a black PVC cylinder (Figure 1). The participants were asked to store the samples safely in a dry and acclimatised environment, to unroll them at least 2 days before testing and to ensure that they were completely flat before testing. Furthermore, the samples were not to be loaded during storage time or during test.

2.3 Measurement procedure

The improvement of impact sound insulation of the floor covering was measured following the application rules of Annex H of ISO 10140-1 [4] on a heavyweight reference floor. The thickness of the concrete reference floors of the laboratories varies between 100 mm and 160 mm (Table 1).
The floor covering was installed loosely on the floor surface. Care was taken that no air was enclosed between the sample and the concrete floor.
Each laboratory performed impact sound insulation measurements according to ISO 10140-3 [9] (Figure 2). The details of the test procedure for each laboratory (number of tapping machine positions and the type and/or number of microphone positions over which averaging is carried out) are reported in Table 1. The tapping machine positions for the measurements on the bare floor had to be chosen identical to the respective tapping machine positions used for the measurement with sample. It was therefore recommended to first measure the impact sound pressure level with the sample present, mark all chosen sample positions and then repeat all measurements on the bare floor on the marked positions.

Figure 2 – Impact sound insulation measurement of bare floor and bare floor with vinyl floor covering

While Annex H of ISO 10140-1 [4] states that three or more samples should be installed on the floor, the three samples were to be treated as if they were samples from different products for the RRT. So no samples could be combined in the same test. Each sample had to be tested in at least 4 tapping machine positions.
In total, 4 tests were performed by each laboratory. To determine the influence of the sample variability and the different measurands on the repeatability, two tests (named test 1 and test 1bis) were performed on sample s1 directly after each other. The test on sample s1 was repeated in its entirety. All parameters were measured again: the sound pressure level with and without sample, the reverberation time (T_r) and the background noise. While ISO 12999-1 states that the set of microphone and source positions should be selected anew, more or less randomly, for each repeated measurement, it was prescribed in this RRT to take the same tapping machine positions, sound source positions (for T_r) and microphone positions for test 1 and test 1bis.

For the tests on sample s2 and s3 (named test 2 and test 3), only the measurements with sample had to be performed. For the sound pressure levels on the bare floor and the reverberation times, the measured values from test 1 are reused. However, the background noise level was measured again.

2.4 Statistical analysis

Each laboratory sent a reporting sheet with laboratory data and measurement results for each of the four tests to the RRT supervisor at BBRI. The predefined reporting sheet contains:

- details on laboratory characteristics and measurement procedure;
- environmental conditions (air temperature, air humidity);
- detailed measurement results (impact sound pressure levels on bare concrete floor, impact sound pressure levels on vinyl floor covering, background noise levels, reverberation times);
- single-number values according to ISO 717-2 [10].

The results for the normalized impact sound pressure levels and the improvement of impact sound insulation are automatically calculated from the detailed measurement results in the reporting sheet to avoid errors. The single-number values were verified by the RRT supervisor and recalculated to one decimal place according to the latest version of ISO 717-2 [10].

The estimates for the general mean, the repeatability standard deviation s_{r} and the reproducibility standard deviation s_{R} have been calculated according to ISO 5725-2 [11] (with the number of laboratories $p = 9$ and the number of replicate tests $n = 4$), without disqualifying any outliers in the results [6]. First, the within-laboratory variance s_i^2 is calculated from the four test results for each laboratory i. The repeatability variance s_{r}^2 is then determined as the average of the s_i^2-values. Finally, the reproducibility variance s_{R}^2 is determined from:

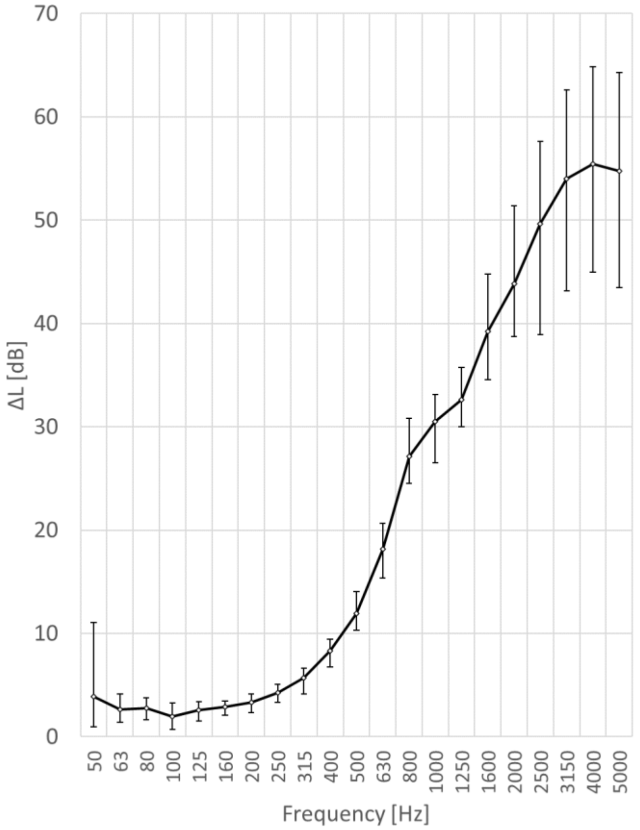
$$s_{\mathrm{R}}^2 = s_{\mathrm{L}}^2 + s_{\mathrm{r}}^2 \quad (1)$$

with s_{L}^2 the between-laboratory variance.

3 Results

The general mean for the improvement of impact sound insulation ΔL of the vinyl floor covering, estimated from all test results from the 9 laboratories, is shown in Figure 3. The vinyl floor covering results in a mean overall improvement of ΔL_{w} = 19.5 dB (with laboratory average values between 18.5 dB and 20.2 dB) and ΔL_{lin} = 9.1 dB (with laboratory average values between 8.2 dB and 9.8 dB). The improvement ΔL is small up to 250 Hz (average improvement of 3 dB) and starts to increase at the cut-off frequency around 315 Hz with approximately 15 dB per octave band. For most of the laboratories, the ΔL-spectrum showed a distinct dip or plateau between 800 Hz – 1250 Hz. Because this plateau was not present in all laboratory results and sometimes shifted by one-third octave band, the plateau is less pronounced in the general mean. The non-linear increase above the cut-off frequency of the soft floor covering may be caused by the resonances in the force spectrum of the tapping machine or by a non-linear response from the vinyl [12]. At high frequencies, the increase in ΔL starts to drop, mainly because the background noise was influencing the measurement results in most laboratories from 2000 Hz – 2500 Hz upwards.

The minimum and maximum values of the laboratory average values are also indicated on the graph. Generally, the spread in laboratory results increases with frequency. At low frequencies, the uncertainty is limited, except at 50 Hz due to one outlier. The large spread above 2000 Hz can be partly explained by the fact that the background noise is influencing the results. In this frequency range, the lowest values were reported by laboratory 7 (which has the smallest floor area of 8.3 m²), although no background noise correction was needed for that laboratory.



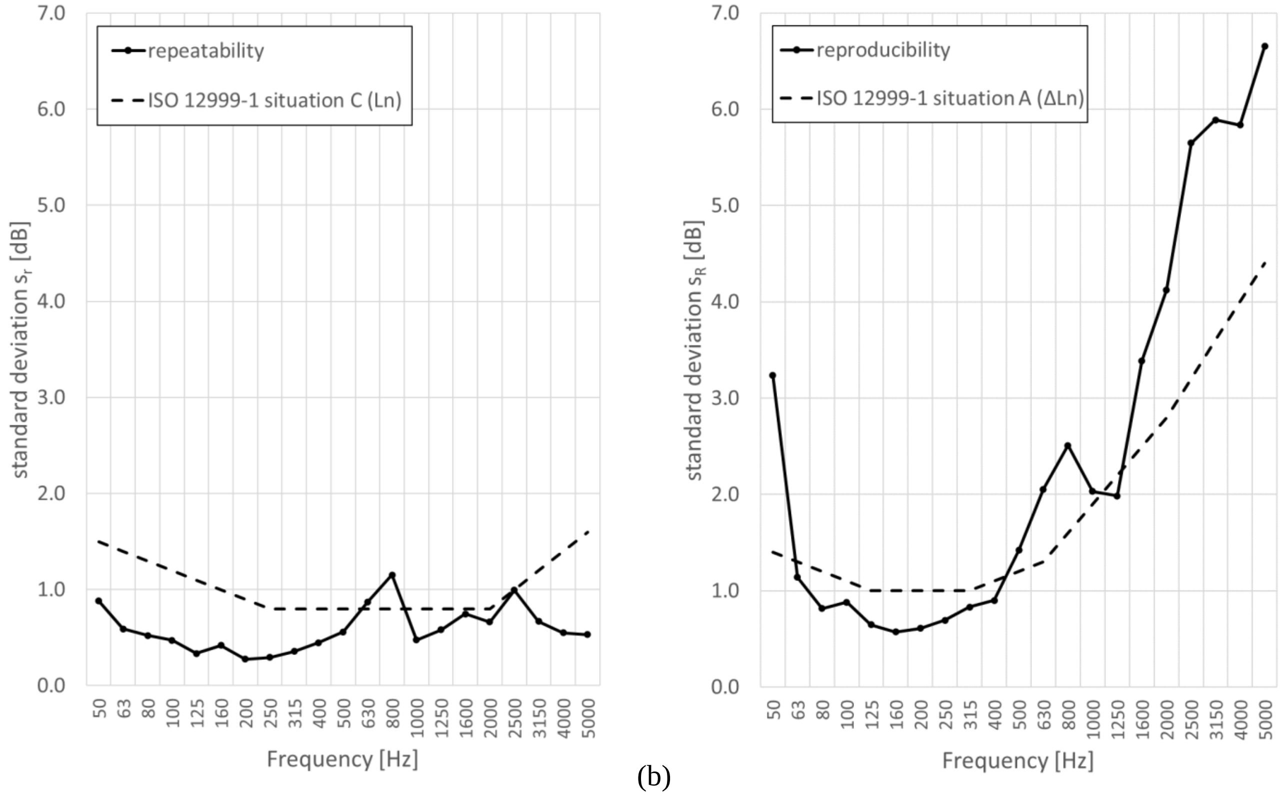
Lab.	ΔL_w [dB]	ΔL_{lin} [dB]
1	19.5	9.2
2	18.5	8.2
3	19.5	9.0
4	19.4	9.1
5	19.9	9.3
6	19.8	9.3
7	19.8	9.3
8	20.2	9.8
9	19.4	9.1
mean	19.5	9.1

Figure 3 – General mean and min-max bars of laboratory average values for ΔL of the vinyl floor covering (left) and average single number ratings for each laboratory (right)

Figure 4 compares the estimated standard deviation under repeatability and reproducibility conditions with the standard uncertainties of ISO 12999-1 [6]. Because no standard uncertainties are currently available for the reduction of impact noise at repeatability conditions, the repeatability standard deviation is compared with ISO 12999-1 values for impact sound insulation (L_n) measurements.

In most frequency bands, the repeatability standard deviation is lower than the ISO 12999-1 standard uncertainty for impact sound insulation at repeatability conditions (Figure 4a). Only around 800 Hz, which corresponds to the frequency at which the plateau starts in the ΔL-spectrum, a larger spread is observed in all laboratory results. This peak is caused by variations in the measurement of L_n with vinyl floor covering (see section 4.2).

The reproducibility standard deviations of the round robin test agree well with the ISO 12999-1 values at low frequencies, but are significantly larger from 500 Hz upwards (Figure 4b). The peak observed around 800 Hz in the repeatability standard deviation is also clearly visible in the reproducibility uncertainty. The large uncertainty at high frequencies is partly related to background noise issues, but probably other factors also play a role, like the contact conditions between the bare floor and the vinyl floor covering which may be different due to irregularities in the bare floor surface (air pockets, dust). The peak at 50 Hz is largely influenced by one outlier, but the uncertainty remains higher than the ISO value even when the outlier is omitted (s_R = 2.1 dB at 50 Hz without outlier).



(a) (b)

Figure 4 – Standard deviation under (a) repeatability and (b) reproducibility conditions for ΔL of the vinyl floor covering.

Table 2 –Standard deviation under repeatability and reproducibility conditions for the single-number values.

Standard deviation	Method 1		Method 2	
	ΔL_w	ΔL_{lin}	ΔL_w	ΔL_{lin}
Repeatability s_r [dB]	0.20	0.19	0.40	0.35
Reproducibility s_R [dB]	0.51	0.47	0.85	0.75

4 Discussion

4.1 Single-number values

The uncertainty associated with single-number values determined in accordance with ISO 717-2 [10] can be determined by two different methods [6]. In the first method, the single-number value is treated as an independent measurand. The standard deviation under repeatability and reproducibility conditions is calculated in the same way as the third-octave band values using the results of the table in Figure 3. In the second method, an upper limit for the uncertainty of the single-number value is calculated assuming full, positive correlation between the one-third octave band values (annex B of ISO 12999-1 [6]).
The estimated standard deviation under repeatability and reproducibility conditions for the single-number values ΔL_w and $\Delta L_{lin} = \Delta L_w + C_{I\Delta}$ are given in Table 2. The uncertainty on the single-number values is very low. ISO 12999-1 gives a standard uncertainty under reproducibility conditions of 1.1 dB for the

weighted reduction of impact noise ΔL_w by floor coverings (as determined by method 1), whereas the uncertainty is only 0.51 dB for this RRT. This can be explained mainly by the fact that the single-number values for the vinyl floor covering are completely determined by the one-third-octave band values between 100 Hz and 500 Hz. In these frequency bands, the standard deviations are low (Figure 4), resulting in low uncertainties for the single-number values.

4.2 Parameters influencing repeatability

Different parameters will influence the repeatability uncertainty of ΔL, like the spatial and temporal averaging of the impact sound pressure levels of the bare floor (L_{p0}) and of the floor with vinyl covering (L_p), the background noise correction, and the determination of the room reverberation time (T_r) which influences the normalized impact sound pressure levels (L_{n0} and L_n). The relative importance of these uncertainties has been investigated by comparing the detailed results of test 1 and test 1bis of each laboratory (Figure 5). At low frequencies (up to 200 Hz), the repeatability uncertainty is mainly caused by the non-diffusiveness of the sound and vibration fields. This has a similar impact on all measured quantities (L_{p0}, L_p, T_r). Due to the additional uncertainty on T_r, the uncertainty for the normalized quantities L_{n0} and L_n is generally larger than the uncertainty for L_{p0} and L_p. At mid and high frequencies, the repeatability uncertainty of ΔL is mainly determined by the uncertainty in the L_p-measurement with vinyl. The room reverberation time can be measured with good accuracy. As a result, the standard deviation for L_{n0} and L_n is smaller than for L_{p0} and L_p, which is theoretically expected when the correction for room absorption is exactly known.

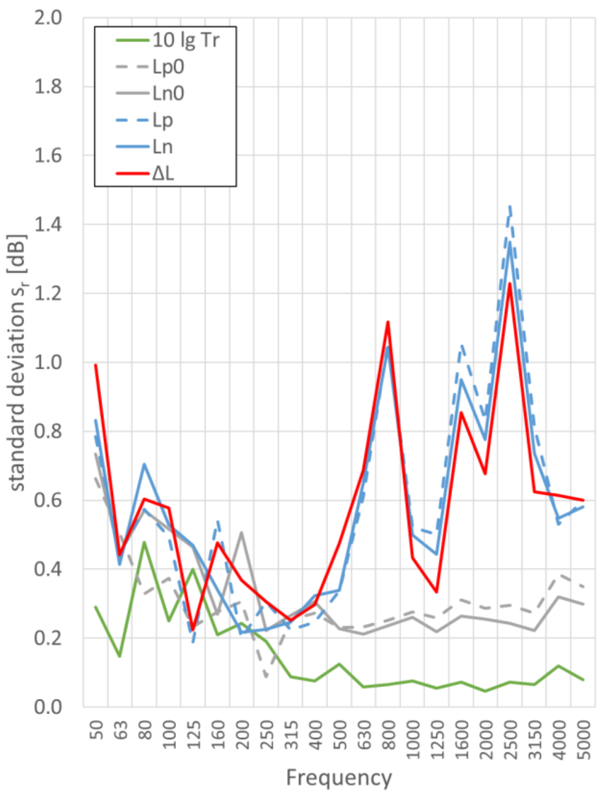


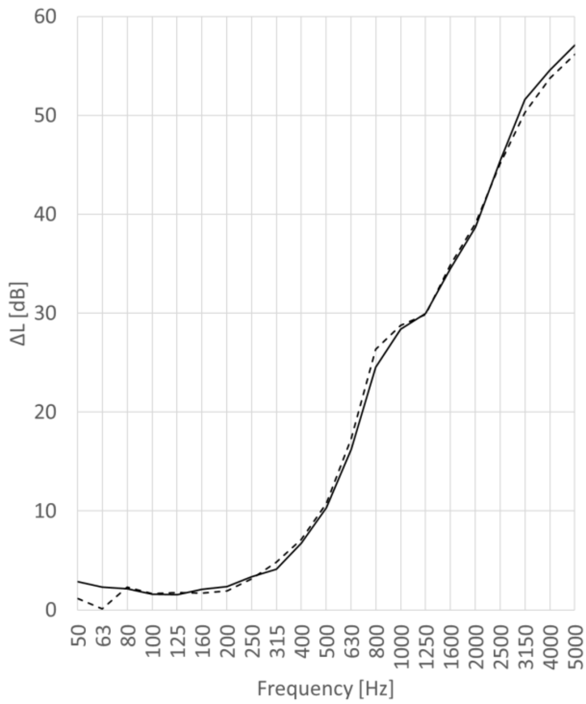
Figure 5 –Standard deviation under repeatability conditions for the different measurands determining ΔL

4.3 Parameters influencing reproducibility

4.3.1 Laboratory characteristics

The laboratory characteristics most likely to influence the reproducibility uncertainty of ΔL are the room geometry, the floor thickness and geometry, the boundary conditions (including the placement of the vinyl on the bare floor) and the bare floor loss factors. The effect of flanking transmission is expected to be small, because it will influence the measurement of L_{p0} and L_p in the same way. The variation in temperature and humidity reported by the laboratories is limited and thus its influence is probably also small compared to other uncertainties.
The results have been investigated in detail, but no systematic deviation could be observed with room volume, floor area or bare floor thickness, both in terms of average ΔL-value or repeatability standard deviation of each laboratory. The bare floor impact sound pressure level L_{n0} depends on the floor thickness and the bare floor loss factor, with values of $L_{n0,w}$ varying between 76.6 dB and 82.1 dB for the 9 laboratories. Nevertheless, no systematic correlation is found between L_{n0} and ΔL. This confirms the theory that the bare floor properties do not influence the ΔL of soft floor coverings [12].
The standard ISO 10140-5 [5] prescribes a minimum loss factor for heavy structures. Four laboratories reported the bare floor loss factor. Not all results fulfil the requirement (Figure 6a). The influence of the bare floor loss factor on ΔL is however very small, as confirmed by two measurements performed at the same laboratory with different edge conditions for the bare floor (Figure 6b). One floor was detached from the surrounding structure by rockwool at its four edges (full black curve), while the joints between the other floor and the surrounding structure was filled with mortar at two sides (dotted black curve), leading to a much higher structural loss factor (Figure 6a, black curves).

(a) Loss factor measured at 4 laboratories and minimum loss factor required by ISO 10140 (red)



(b) Influence of the bare floor edge conditions on ΔL

Figure 6 –Influence of the structural loss factor of the bare floor

4.3.2 Sample variability

Because all laboratories received different test samples, the variability among the test samples due to their heterogeneity forms an inherent part of the reproducibility standard deviation. It was however assumed that the sample variability is negligible because all samples were cut from the same vinyl floor covering and thus nominally identical. Furthermore, the variability is levelled out because all laboratories received three randomly chosen samples. This seems to be confirmed by the RRT results. Figure 7 compares the repeatability standard deviations for L_p calculated from three different data sets. The first one is determined from the results of test 1 & 1bis, for which the same sample was used. The other are determined from the results of test 1 & 2 and test 1 & 3, for which different, but nominally identical samples were used. If the sample variability is important, a smaller uncertainty is expected for the first data set (test 1 & 1bis), but this is not systematically the case over the frequency range of interest. Only between 315 Hz and 630 Hz, the sample variability may play a small role.

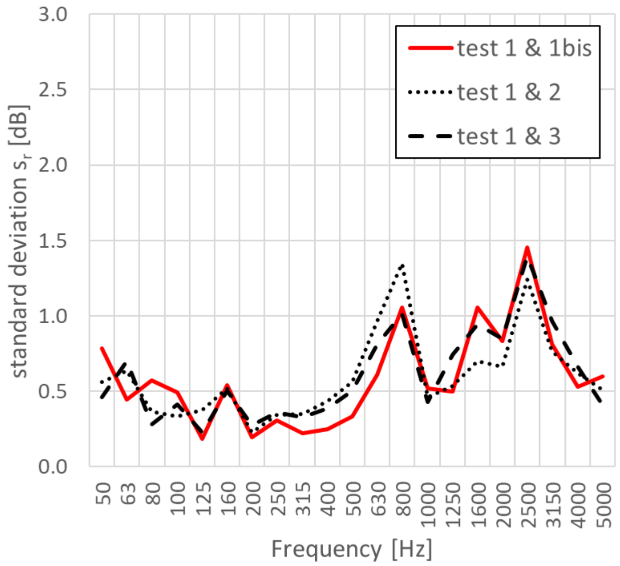


Figure 7 – Standard deviation for L_p under repeatability conditions for the same sample (test 1 & 1bis) or different samples (test 1 & 2 and test 1 & 3).

5 Conclusions

To obtain data on repeatability and reproducibility as input for ISO 12999-1, an inter-laboratory test was organized for the improvement of impact sound insulation. The RRT does not fulfil all requirements for inter-laboratory tests of ISO 12999-1 and ISO 5725-2. To limit the measurement effort, the number of repeated measurements in each laboratory was limited to four. Furthermore, the quantities L_{p0} (impact sound level of bare floor) and T_r (reverberation time) were nor remeasured for sample s2 and s3. Nevertheless, the repeatability uncertainty can be well estimated from the four repeated measurements because the uncertainty for ΔL is mostly determined by the uncertainty in the measurement of L_p (impact sound level with vinyl floor covering). The sample variability is small because all samples were cut from the same vinyl floor covering. The reproducibility uncertainty determined in this RRT is thus mainly caused by the differences in the laboratory characteristics (room and floor geometry, boundary conditions, background noise, …). Another parameter which may influence both the repeatability and reproducibility is the surface contact between the bare floor and the vinyl, as small irregularities (dust, air pockets) can influence the improvement in impact sound insulation.

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