On the Low Frequency Impact Noise Measurement in Residential Buildings

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Abstract. We commonly encounter cases that, despite the fact that buildings meet normative requirements, people are disturbed by unwanted noise generated by walking and other sources of impact noise. It is not unusual that in practice the designer often moves on the edge of the required criteria in order to reduce the cost of constructions and its parts. In this article, we selected 4 blindly chosen cases of flats where complaints from residents about high levels of impact noise were recorded although the construction meets the requirements set out in the standard. Based on the obtained documentation of in-situ performed measurements by different consulting companies, BEM and FEM models were created, and the distribution of acoustic pressure in an enclosed space and compared different methods of spatial averaging of the resulting acoustic pressure were simulated. The aim of this analysis is to point some of the reasons for possible user complaints about the impact noise despite normative requirements. The usual problems are benevolent national requirements and the issue of measuring noise in the low frequency range and underestimating its significance. The article also discusses the currently set requirements for the evaluation of floor structures in selected countries.

1. Introduction
The propagation of low-frequency (LF) noise in buildings is a common topic in building acoustics nowadays. In practice, we commonly encounter cases that, despite the fact that buildings meet normative requirements, people are disturbed by unwanted noise generated by walking and other sources of impact noise. This is one of the reasons why it is one of the main topics of subjective perception in building acoustics, and investigations are performed mainly on the basis of listening tests [1]. However, these complaints from building users can be avoided by the correct design of construction solutions. Depending on the nature of the ceiling structure, layers with the suitable mass and dynamic stiffness properties must be correctly chosen so that the resonant response of the mass-spring-mass system is as low as possible, the amplitude of the resonance caused vibrations is attenuated as much as is possible and the individual layers do not resonate separately. However, it is not unusual that in practice the designer often moves on the edge of the required criteria in order to reduce the cost of constructions and its parts. Despite the efforts of international organizations to unify the requirements for partition structures we still encounter different requirements in building acoustics, including impact noise. This diversity was documented as early as 2010 and many major changes have not taken place since [2-9](Fig.1). There must be noted, the differences up to 21dB in required values for acceptable impact noise
in new dwelling houses shown in the colour map can be partially caused by different descriptors used in countries (Tab.1). Generally, the weighted standardized impact sound pressure level $L'_{nT,w}$ gives usually lower results than weighted normalized impact sound pressure level $L'_{n,w}$. Also taking into account the low frequency spectra via adaptation terms $C_i$ and $C_{1,50-2500}$ can make large difference in the results mainly in case, when the floor/ceiling responses dominantly in the low frequency range.

![Figure 1. Difference in requirements on maximal acceptable impact noise level in new dwelling houses in chosen European countries (the colour bar shows the value of a descriptor corresponding to the country in dB).](image)

We often distinguish whether it is a new building or a reconstruction and in which frequency range we assess the quality of the structure. Floors are usually evaluated in the frequency range from 100 to 3150Hz. However, experience shows that in order to avoid complaints, it is better to assess building structures in the range from 50Hz. This is still only an optional in most countries.

| Country                              | Descriptor                          |
|--------------------------------------|-------------------------------------|
| Bulgaria, Denmark, Estonia, Germany, Latvia, Czech Rep., Hungary, Serbia, Iceland, Slovenia, Romania, Portugal, Italy, Croatia, Slovakia, Austria, Poland, Scotland, England, Wales, Belgium, France, Ireland, Spain, Switzerland, Netherlands, Sweden, Finland | $L'_{n,w}$ or $L'_{nT,w}$             |
|                                      |                                     | $L'_{n,w}$ or $L'_{nT,w}$ + $C_i$     |
|                                      |                                     | $L'_{nT,w}$ + $C_{1,50-2500}$         |

It is well-known that with decreasing frequency, measurement uncertainty very often increases which is caused by non-diffuse sound filed in the room. This is directly related to the low modal density of these enclosed spaces. This adverse effect can be neglected, for example, by using some of vibrometric techniques [10]. These methods have nowadays the best possible use in development in the laboratory or in the detection of defects in construction. However, the disadvantage here is in particular the time-consuming nature of such measurements. When measuring the sound pressure level on the construction site, we should not try to neglect the influence of the receiving room, as this can strongly affect the...
subjective perception of the user. It should therefore be noted here that although measurement in a wide range of spectra is necessary, it is also necessary to provide a measurement procedure ensuring sufficient repeatability and reproducibility but, on the other hand, the measurement procedure should not be time consuming. The issue of repeatability of measurements of the sound pressure level was investigated by Hopkins and Turner [11,12]. In 2005, they published recommendations to supplement the procedures of the current standard on in-situ sound pressure level measurements in the low frequency range. It was recommended measurements below 100Hz may be performed by measuring in spatial averaging in the room in combination with measuring in corners at a distance of 0.5 to 0.6m from the corners. They also recommended to use procedure for rooms with volume smaller than 50m³. The problem of measuring only in one plane when the measurement can be strongly influenced by some of the so-called nodal points of the acoustic room modes often occurs. Their recommendations were subsequently partly incorporated into the standard [13], which now recommends the “corner measurements (low frequency measurement procedure)” in spaces smaller than 25m³ and the measurements in corners to perform in distance from 0.3 to 0.4m. The resonant response of the vast majority of ceiling structures is in the range of low frequencies. Therefore, appropriate attention should be paid to low frequency measurements. We can often encounter complaints from residents in cases where adaptation terms are not taken into account, measurements are performed only in one plane or corner measurements are ignored. In this article, we selected 4 cases of flats where complaints from residents about uncomfortable levels of impact noise were recorded although the construction meets the requirements set out in the national standard [5]. Based on the obtained documentation of in-situ performed measurements by different consulting companies, BEM (Boundary Element Model) models were created where the distribution of acoustic pressure in an enclosed space were simulated and different methods of spatial averaging of the resulting acoustic pressure were compared. Additionally, the FEM (Final Element Model) were created for acoustic modes analysis. The aim of this analysis was to point out some reasons for possible user complaints about the impact noise despite the fact it meets normative requirements.

2. Case study description

All 4 selected cases discussed in this paper were rooms in dwelling houses in Bratislava, Slovakia. Despite the acoustic measurements performed according to the standard [13], apartment users complained about disturbing impact noise propagated from their neighbours. In this case study, we focused on the distribution of sound pressure in a receiving rooms of various shapes and dimensions. We monitored the dependence of the position of selected measuring points on the spatial averaging of the resulting sound pressure. Room volumes ranged from 34 to 99m³ with ceiling heights ranging from 2.52 to 2.88m (Table 2).

![Figure 2. Measured $L'_n$ spectra of investigated cases.](image1)

![Figure 3. Example of comparison of the determined STD on the measurement and prediction basis (case 1) according to the theory [14], including room modes in the range from middle frequency 50 to 100Hz.](image2)
Based on the data obtained from $L'_{n,w}$ field measurements, the so-called Schroeder frequency was calculated and numerical models were created. For example in Slovakia the maximum allowable value of $L'_{n,w}$ between apartments is 55dB and in 58dB in new and refurbished dwelling houses respectively. To provide complete information, the measured $L'_n$ spectra including the single number quantities $C_l$ and $C_{50-2500}$ from in-situ measurements of individual cases are shown in the figure 2. In Slovakia, adaptation factors are usually not taken into account all the measurements are giving the results fulfilling the national requirements.

| Room 1 | Room 2 | Room 3 | Room 4 |
|--------|--------|--------|--------|
| Shape  |        |        |        |

| Volume (m$^3$) | 75.4 | 34.2 | 37.2 | 99.3 |
| $h$ (m)       | 2.68 | 2.52 | 2.65 | 2.88 |
| $f_{\text{Schroeder}}$ (Hz) | 198.4 | 226.4 | 278.8 | 170.6 |

Mode 1: 20.1, 20.6, 20.8, 19.4
Mode 2: 27.8, 42.7, 40.0, 25.9
Mode 3: 30.2, 54.1, 52.0, 31.4
Mode 4: 46.3, 67.7, 63.2, 43.4
Mode 5: 54.7, 68.4, 65.3, 47
Mode 6: 59, 79.6, 75.2, 50.1
Mode 7: 64.6, 81.9, 78.2, 52.8
Mode 8: 67.3, 86.6, 82.6, 60.2
Mode 9: 67.8, 95.7, 88.4, 63.2
Mode 10: 69.5, 97.6, 90.3, 64.1
Mode 11: 73.6, 106.4, 101.5, 66.1
Mode 12: 75.7, 106.5, 102.3, 64.1
Mode 13: 78.7, 114.1, 109.6, 75.4
Mode 14: 84, 118.9, 113.7, 75.7
Mode 15: 86.9, 122.6, 120.1, 78.1
Mode 16: 90.53, 126.3, 121.1, 79.3
Mode 17: 92.5, 132.8, 127.6, 80.2
Mode 18: 92.8, 133.7, 129.6, 84.0
Mode 19: 97.4, 134.2, 130.9, 85.0
Mode 20: 99, 136.0, 133.6, 87.5

As the frequency decreases, the measurement standard deviation (STD) increases. For illustration, the figure 3 shows the measurement results from Case 1 in LF spectra up to 200Hz with the plotting of the measurement STD as well as the room modes in range from 50 to 100Hz (middle frequency in 1/3rd octave band). We compared the STD from the measurement with the prediction according to the theory [14]. We can already see the actual measurement uncertainty is significantly higher than the predicted one. In addition to the error of the prediction model, this may be associated with inappropriate spatial averaging during the measurement. In the following text, we only deal with the results of the simulations. In order to determine the modal density of individual spaces, their acoustic modes were predicted (Table 2). Cases were simulated when a plane source (vibrating surface of $S=1m^2$ with magnitude of $v=1m/s$) at the ceiling generates acoustic power radiating into individual rooms. In the models, the sound absorption of surfaces was defined on basis of the measured average acoustic absorption, from which we subsequently defined the corresponding surface impedance. To compare the methods of determining the spatially averaged sound pressure level, following data grids were created:

- Case 1 – Fine grid spaced from all boundaries of 0.1m. Datapoint spacing was 0.3m (default).
- Case 2 – ISO grid based on standard requirements- Distance from the ceiling was 1m and all other boundaries 0.5m. Datapoint spacing of all further cases was set to 0.7m.
• Case 3 – Reduced ISO grid - Distance from the ceiling, floor and walls was 1m; 1.2m and 0.5m respectively.
• Case 4 – The horizontal plane grid – Distance from the floor and vertical boundaries was 0.5m.
• Case 5 – The horizontal plane grid - Distance from the floor and vertical boundaries was 1m and 0.5m respectively.
• Case 6 – The horizontal plane grid - Distance from the floor and vertical boundaries was 1.5m and 0.5m respectively.

Data were also collected in the corners of the rooms in two variants (A-at distance 0.3 to 0.4mm and B-0.5 to 0.6m from the corner boundaries). Based on them, the results were supplemented with the so-called procedure for low frequency measurement (LFMP) for frequency bands 50, 60 and 80Hz (according to the standard) and also for the range from 50Hz to so-called Schroeder frequency. Data processing was always performed (except the “default”) by averaging the values from 5 selected points. More specifically, all of the possible combinations of datapoints groups (were every time each consists of 5 points) for each case were calculated, averaged and their median was taken.

Figure 4. Visualisation of example of the datapoint grids (from the left): Case 1 to 6.

3. Results
At the first look at the presented results, the unusually high values of $L_p$ in the individual spaces analyzed can be recognized. This is due to the noise plane source definition which was modelled with an amplitude of 1(m/s), where the area of the source was always 1m$^2$. However, this does not affect the essence of the analysis, as the aim was to monitor the influence of different methods of spatial averaging $L_p$. The individual cases were compared: without applying the measurement procedure in the low frequency range (LFMP) / with LFMP for 1/3 octave bands of 50, 60 and 80Hz / with LFMP for 1/3 octave bands from 50Hz to $f_{\text{Schroeder}}$ (Fig 5 to 8). For better readability, the first comparison in the following figures always shows the absolute levels of $L_p$ with the indication of the maximum and minimum recorded values in the rooms. Other comparisons are presented as differences with respect to the “default” case 1.
Figure 5. Comparison of spatially averaged $L_p$ spectra - Room1 in the range from 50 to 400Hz. (left) $L_p$ without taking into account the LFMP (low frequency measurement procedure); (centre) $\Delta L_p$ with taking into account the LFMP (for 50,60,80 Hz); distance of data points 0.3 to 0.4m – solid line and 0.5 to 0.6- dashed line from the corner boundaries; (right) $\Delta L_p$ with taking into account the LFMP (from 50Hz to $f_{Schroeder}$); distance of data points 0.3 to 0.4m – solid line and 0.5 to 0.6- dashed line from the corner boundaries;

3.1. Data processing without LFMP

Looking at all the cases, in the spectra below 100Hz, case 2 and case 4 are closest to the “default” case 1. However, in the range above 100 Hz, case 4 is fundamentally deviating from the default values (Fig. 5 to 8, left). Especially in the area with a middle frequency of 200Hz, there is a significant drop in the level. Here, as for all other plane grids, the measured values are strongly affected by the vertical modes of the individual rooms derived from their first mode ($f_{case1}$=64.6Hz; $f_{case2}$=68.7Hz; $f_{case3}$=65.3Hz; $f_{case4}$=60.2Hz). This phenomenon is most noticeable in the region of 100Hz, when with the rising datapoint plane of measurement node in the middle of the height of the room is reached, which causes low measured values. The observed negative effect was 3 to 10dB. Ignoring measuring points below height of 1.2m (Case 3) also results in underestimation of resulting spatially aberaged $L_p$ in the region below 100Hz.

Figure 6. Comparison of spatially averaged $L_p$ spectra – Room2 in the range from 50 to 400Hz. (left) $L_p$ without taking into account the LFMP; (centre) $\Delta L_p$ with taking into account the LFMP (for 50,60,80 Hz); distance of data points 0.3 to 0.4m – solid line and 0.5 to 0.6- dashed line from the corner boundaries; (right) $\Delta L_p$ with taking into account the LFMP (from 50Hz to $f_{Schroeder}$); distance of data points 0.3 to 0.4m – solid line and 0.5 to 0.6- dashed line from the corner boundaries;

3.2. Processing including LFMP for 50, 60 and 80Hz middle frequencies

The influence of modifying the spatial averaging by data from the corners of the analyzed spaces was studied (Fig. 5 to 8, centre). The one-third octave spectrum from 50 to 80 Hz was modified so that the differences in the $L_p$ level were suppressed to max 3dB deviations from the default case. When comparing the choice of points A or B, that can be stated, by choosing a closer distance from the corner the $L_p$ at frequencies below 100Hz is overestimated which is in favor of security. As a result, only for case 2 and case 4 there was a more significant relative exceedance (up to 2dB) of average $L_p$ compared to case 1 (default). That the approach recommended by the ISO standard (0.3 to 0.4m distance from the corners) results in “safer data” than the choice of measured points at a distance of 0.5 to 0.6m from the corners in all analyzed cases. It is also worth noting that the LFMP favorable effect ends at 80Hz which as a result can be seen as a sudden drop in $\Delta L_p$ at 100Hz. This motivated the authors to implement LFMP even for higher frequencies up to the area where a diffuse sound field is assumed.
Figure 7. Comparison of spatially averaged $L_p$ spectra – Room3 in the range from 50 to 400Hz. (left) $L_p$ without taking into account the LFMP; (centre) $\Delta L_p$ with taking into account the LFMP (for 50,60,80 Hz); distance of data points 0.3 to 0.4m – solid line and 0.5 to 0.6- dashed line from the corner boundaries; (right) $\Delta L_p$ with taking into account the LFMP (from 50Hz to $f_{Schroeder}$); distance of data points 0.3 to 0.4m – solid line and 0.5 to 0.6- dashed line from the corner boundaries;

3.3. Processing including LFMP for 50Hz to $f_{Schroeder}$

Furthermore, the influence of modifying the results by data from the corners of the analyzed spaces was studied (Fig. 5 to 8, right) in the frequency range from 50Hz to $f_{Schroeder}$. It is worth considering why the standard calculates with the LFMP measurement procedure only in the range up to 100Hz, when the diffusion of space (assumed in most microphone measurement methods used in building acoustics) assumes only in the spectrum above $f_{Schroeder}$. The same trend as in the previous case can be observed here. There is a major improvement - shifting the average $L_p$ spectrum closer to the default. In some cases, improvement of spectra up to 10 dB can be recognized in specific region. The procedure inspired by the standard results in “safer data” as the choice of measured points at a distance of 0.5 to 0.6 m from the corners in all analyzed cases.

Figure 8. Comparison of spatially averaged $L_p$ spectra – Room3 in the range from 50 to 400Hz. (left) $L_p$ without taking into account the LFMP (low frequency measurement procedure); (centre) $\Delta L_p$ with taking into account the LFMP (for middle frequencies 50,60,80 Hz); distance of data points 0.3 to 0.4m – solid line and 0.5 to 0.6- dashed line; (right) $\Delta L_p$ with taking into account the LFMP (from 50Hz to $f_{Schroeder}$); distance of data points 0.3 to 0.4m – solid line and 0.5 to 0.6- dashed line;
4. Conclusion
The impact noise measurement procedures are defined in the standard [13]. Experience has shown that the quality of the ceilings is determined by the measured values, especially in the area of low frequencies. This is also reflected in the complaints of users who always complain about low-frequency noise (impact noise is always low-frequency). The presented paper pointed out the need to take into account the LFMP precisely. By ignoring this procedure and placing the measuring points in narrow areas, the low-frequency energy generated by the impact source can be inadvertently neglected. The analysis also showed that the results obtained based on spatial averaging in case 1 (the fine grid – default case) are closest to those obtained with the procedures in accordance with ISO16283-2. The standard also recommends performing LFMP measurements at a distance of 0.3 to 0.4m from corner boundaries. However, the LFMP is used only for the frequency range below 100Hz, while it would possibly find application in the whole non-diffuse frequency spectra (up to Schroeder frequency). All of the analyzed spaces were, however, of volume larger than 25m$^3$ (in accordance to standards it is not required to perform LFMP). Nevertheless, the analysis showed that this procedure has an effect even in rooms up to 100 m$^3$. Moreover, the large variation of requirements on the impact noise level in dwelling houses (up to 20 dB) in European countries raises assumptions that in some countries the requirements are underestimated.

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