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INVESTIGATING OBJECTIVE APPROACHES FOR ASSESSING IMPACT SOUND INSULATION IN CEILING SYSTEMS UNDER HEAVY/SOFT IMPACT EXCITATION

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Abstract

Objective evaluations of ceiling constructions are becoming increasingly significant due to advancements in the construction industry and rising resident complaints, particularly those concerning disturbances from low-frequency noise (<100 Hz). It is important to determine the required values for the maximum impact noise level in residential buildings. While the standard outlines a procedure for determining this level, there are no specific requirements for ceiling constructions related to heavy excitation sources. This study compares four different approaches for rating noise levels in the frequency range of 50 to 630Hz based on LA,Fmax. Through a numerical case study, the research reveals a linear deviation in the ISO-defined procedures based on a room's volume and reverberation time, while also highlighting the differences in the outcomes of the evaluation between the four methods due to their distinct reference curve approaches. The findings indicate that no single evaluation procedure has emerged as definitively more reliable, thereby emphasizing the need for further investigation into the perception of impact noise and the establishment of standardized requirements.

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Key words

- Building acoustics,
- Impact noise,
- Heavy / soft impact sources,
- Parametric study.

1 INTRODUCTION

The objective evaluation of ceiling constructions remains a relevant research topic. It has been driven by advancements in the construction industry and a rise in complaints from residents (Rindel and Rasmussen, 1997; Rasmussen and Petersen, 2024; Andargie et al., 2023). A frequent concern is disturbances, particularly those coming from noise below 100 Hz. In response, several countries have established requirements for ceiling structures that address not only the single number quantity (SNQ) but also the mass-spring-mass resonance frequency of a floor (OEN, 2021, STN, 2024). In contemporary Europe, the assessment of the impact sound insulation of a ceiling structure involves the use of excitation devices and procedures specified in standards ISO 10140-3 (ISO, 2021a), ISO 10140-5 (ISO, 2021b), ISO 16283-2 (ISO, 2020a), and ISO 717-2 (ISO, 2020b). The standardized sources of impact noise include a standard tapping machine, a modified tapping machine, and a heavy/soft impact source, such as a rubber ball. The objective parameters typically obtained from measurement procedures in accordance with ISO standards are $L'_{nT,w}$ (the weighted standardized impact sound pressure level), $L'_{n,w}$ (the weighted normalized impact sound pressure level), $L'_{iA,Fmax}$ (the A-weighted maximum impact sound pressure level), and $L'_{iA,Fmax,V,T}$ (the standardized A-weighted maximum impact sound pressure level). Despite the fact that the ISO standards also define the procedure for evaluating and testing ceiling structures on the basis of excitation from a heavy source (a rubber ball) through one of the forms of expression of the maximum value of the acoustic pressure level, nowadays we do not register requirements applying to ceiling structures in apartment buildings in the individual European countries (Rasmussen and Machimbarrena, 2014; Rasmussen, 2022; Rasmussen, 2019). The assessment of maximum sound pressure levels is only encountered in connection with the assessment of the acoustics of living spaces related to technical service equipment, etc., from the point of view of hygiene criteria (OIB, 2023). However, the assessments do not impose specific requirements on ceiling structures. As has already been demonstrated, it is not possible in specific cases to excite the ceiling structure strongly enough to be able to evaluate it objectively, especially in the frequency spectrum below 100Hz (Urbán et al., 2024; Hopkins, 2012). Moreover, performing acoustic measurements in enclosed spaces in the frequency range below the so-called Schroeder's frequency is also a separate topic, whether in connection with an evaluation of the quality of the environment or any dividing structures (Urbán and Zaťko, 2021; Roozen et al., 2015; Roozen et al., 2018). However, this is not directly related to the excitation source. A heavy/soft impact sources such as a rubber ball is spectrally more similar to the noise generated by a child's stomping or walking with bare feet (Jeon et al., 2006). In scientific publications that explore the subjective perception of impact noise levels, we frequently find other objective evaluation parameters (Jeon et al., 2006), which have prompted us to investigate the JIS A 1418-2 (JIS, 2019), JIS A 1419-2 (JIS, 2017) and KS F2810-2 (KS., 2022), standards that specifically address this issue.

Despite the fact that sound insulation evaluations of structures are globally conducted not only in accordance with ISO or JIS standards but also with the approaches defined in the ASTM standards (Rindel, 2017; AST, 2021c; AST, 2016; AST, 2021a; AST, 2021b), this article will focus exclusively on comparing the procedures defined in the ISO, JIS, and KS standards. We also do not want to question with this publication the relevance of a single number rating based on tapping machine excitations. Currently, it is common in practice to assess ceiling structures using the spectrum adaptation term $C_{I,50\text{-}2500}$ in accordance with ISO 717-2 (ISO, 2020b). This spectrum adaptation term $C_{I,50\text{-}2500}$ is applicable not only in cases of light ceiling structures, but is also of great importance in the application of heavy floating floors (Hosoien et al., 2016). It also definitely has a place in the development of the classification of ceiling structures in the form of classes (del Val et al., 2018). Extensive studies (Ljunggren and Simmons, 2022; Ljunggren et al., 2014), which focused on the correlation between sound insulation and the occupants' perception, have also demonstrated a need to evaluate structures by taking $C_{I,50\text{-}2500}$ into account. They also focused on alternative spectrum adaptation terms with ratings starting from 20 and 25Hz respectively. Here, an even higher correlation with the subjective perception of the occupants was demonstrated. However, the problem here may be the high uncertainty of determining measurements in the low frequency range, which is also reflected in the determination of $C_{I,50\text{-}2500}$ itself (Anónio and Mateus, 2015), and also the weak excitation of structures in the low frequency range when using a tapping machine. This may ultimately give the impression that spectrum adaptation factors are not important, which is not true.

This paper presents a comparative analysis of various methods for single number assessments of impact noise insulation based on heavy/soft source excitations. The contribution is structured into the following basic parts: a description of the sound sources, a description of the measurement procedures in accordance with ISO, JIS and KS, an explanation of the assessment procedures, a description of a numerical case study, and a mutual comparison of the methods. The motivation for this article was to deepen interest in the field of the use of heavy/soft impact sources in evaluations of ceiling structures and to reflect different approaches to the determination of single-number objective indicators. This article follows on from a study previously presented (Urbán, 2024) and aims to enhance the understanding of and encourage future research in the objective assessment of ceiling structures, particularly regarding heavy/soft impact sources.

2 DESCRIPTION OF SNQ DETERMINATION BASED ON SELECTED STANDARDS

In the 1970s, countries such as Japan and South Korea had already introduced measurement procedures for evaluating ceilings using heavy excitation sources like a rubber ball and a device using a car tire, also known as a "bang machine". A few years later, ISO adopted one of these sources (a rubber ball) and procedures as alternatives to tapping machine excitations. In this part, the so-called "heavy/soft excitation" sources will be gradually characterized; the measurement procedures will be explained; and then the procedures used in the single-number evaluations and a brief summary of the requirements will be presented.

2.1 Characterisation of a heavy/soft source: a rubber ball

As similarly stated in both the ISO, JIS and KS standards, the standardized hollow rubber ball can be characterized as a silicone ball with a diameter of 180 mm, a wall thickness of 30 mm, and a weight of 2.5 ± 0.1 kg. The standardized ball must have the character of the exposure spectrum of the impact force within the limits shown in (Fig. 1). During a test of the ceiling structure, the ball is released by a free fall onto the tested structure from a height of 1 ± 0.1 m. This vertical distance is measured between the bottom of the ball and the surface of the ceiling structure. The ceiling structure is excited in at least 4 positions. In the case of testing wooden ceilings, one of the excitation positions is in the middle, and one is above the joint of the ceiling structure. In an objective evaluation of a ceiling structure, the maximum sound pressure level L'_{Fmax} in dB is measured using a "Fast" time constant in at least 4 positions of a microphone for each excitation position (ISO, 2021a). On the other hand, the JIS A 1418-2 (JIS, 2019) recommends measurements in three to five positions. For measurements in the 1/3rd octave band, the measurement range is from 50 to 630Hz in accordance with ISO 10140-3. The JIS A 1418-2 also mentions the possibility of extending the measurement range down to 25Hz. Subsequently, the spatially averaged maximum sound pressure level in the receiving room $L'_{i,\,Fmax}$ and, if necessary, the spatially averaged reverberation time, are expressed. Exact guidance regarding the distribution of the source and receiver positions is given in ISO 10140-3 (ISO, 2021a) and JIS A 1418-2 (JIS, 2019).

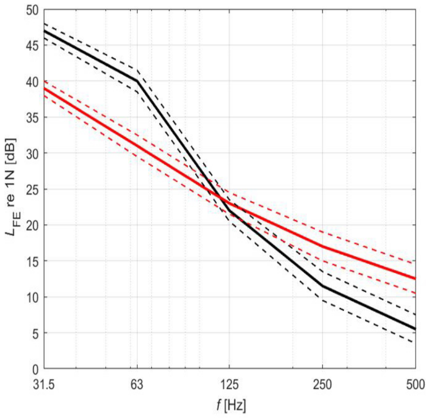

Fig. 1 *Impact force exposure level (L_{FE}) in the octave band spectra of the heavy/soft impact sources (ISO, 2021b, JIS, 2019). Red - rubber ball; Black - bang machine.*

2.2 Characterisation of a heavy/soft source: a Bang machine

The JIS A 1418-2 standard recognizes the so-called "Bang machine" as the primary excitation source of impact noise. It is an automated mechanism, where the excitation part consists of an air-filled tire ((2.4 ± 0.2) × 105 Pa) with an effective weight of 7.3 ± 0.2 kg. A tire that is usually attached to an automatic arm is dropped by free fall from a height of 85 cm; in addition, there is a strict need to maintain the tire pressure. The other guidelines are the same as for the rubber ball according to the JIS A 1418-2. At this point, we must not forget the KS F 2810-2 (KS., 2022) standard, which defines the sources and the measurement procedure similarly. It also discusses the compensation for the effect of high background noise on measurements with heavy sources. Background noise correction is already applied in cases of a signal-to-noise ratio (SNR) of 14 dB or less.

2.3 Determination of SNQ in accordance with ISO 717-2 and ISO 10140-3

The primary (normative) excitation source of impact noise in accordance with the ISO standards for testing ceiling structures is the use of a standard tapping machine (sometimes also called a "light impact source"). We only recognize the heavy/soft source as an alternative source in the form of a rubber ball. Based on the data obtained using the measurement procedures described in the above section, two single-number quantities can be generally determined for heavy/soft sources. We encounter a single-number quantity (SNQ) in the form of the A-weighted maximum impact sound pressure level $L_{iA,Fmax}$ (or $L'_{iA,Fmax}$ for measurements in buildings) and a single-number quantity (SNQ) in the form of the standardized A-weighted maximum impact sound pressure level $L_{iA,Fmax,V,T}$ (or $L'_{iA,Fmax,V,T}$ for measurements in buildings). The SNQ is determined as the total maximum sound energy weighted by the filter A (1).

$$X_{iA,Fmax} = 10lg \sum 10^{\frac{X_{iA,Fmax,j}+A_j}{10}} \tag{1}$$

Where $X_{iA,Fmax}$ is the rounded integer of $L_{iA,Fmax}$, $L'_{iA,Fmax}$, $L_{iA,Fmax,V,T}$, and $L'_{iA,Fmax,V,T,\ j}$ is the subscript of the frequency bands; $X_{iA,Fmax,j}$ is the specific maximum level (one of the four possibilities mentioned above) to one decimal place; and A_j is the A-weighting correction for the specific frequency band. The determination of the standardized A-weighted maximum impact sound pressure level $L_{iA,Fmax,V,T}$ is preceded by the determination of the standardized maximum impact sound pressure level $L_{i,Fmax,V,T}$. This quantity spectrally expresses the maximum noise level with the aim of suppressing the effect of the sound absorption and receiving the room volume on the objective acoustic assessment. $L_{i,Fmax,V,T}$ can be expressed as(2):

$$L_{i,Fmax,V,T} = L_{i,Fmax} + 10lg\frac{V}{V_0} - 10lg\left[\frac{1-C_0^{-1}}{1-C^{-1}}\left(\frac{C^{(1-C)^{-1}} - C^{-(1-C^{-1})^{-1}}}{C_0^{(1-C_0)^{-1}} - C_0^{-(1-C_0^{-1})^{-1}}}\right)\right] \tag{2}$$

Here, V and V_0 indicates the receiving room volume in m^3 and the reference receiving room volume for dwellings (V_0=50 m^3). C and C_0 are defined based on the reverberation time in the receiving room T and the reference reverberation time (for dwellings, T_0=0.5 s) as $C=T/1.7275$ and as $C_0=T_0/1.7275$.

2.4 Determination of SNQ in accordance with JIS 1419-2

It is important to note that ISO 717-2 and JIS A1419-2 are technically similar except for the three Annexes. In the following subsections, the individual assessment methods are briefly explained according to the appendices.

2.4.1 Evaluation of the performance of the floor impact sound insulation of buildings using grade curves

According to the JIS, the grade curve evaluation method is normative and is applicable both to standardized tapping machines and heavy/soft sources. For an evaluation of the data obtained by tapping machine excitation, depending on the input spectrum of the physical quantity (impact sound level Li, normalized floor impact sound level L'_n, and standardized floor impact sound level L'_{nT}), the impact sound level grade $L_{i,r}$, normalized floor impact sound level class $L'_{n,r}$, or standardized floor impact sound level class $L'_{nT,r}$ is determined. In the case of excitation by a heavy/soft source, the maximum sound pressure level grade $L_{i,Fmax,r}$ is determined from themaximum sound pressure level $Li_{,Fmax}$.

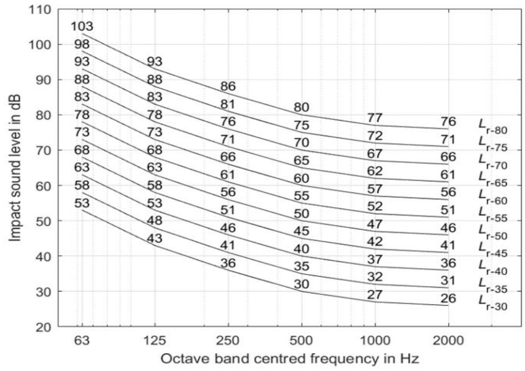

Fig. 2 *Grade curves in accordance with JIS A 1419-2 (JIS, 2019)*

The evaluation into classes is performed in a full-octave frequency band for tapping machines from the octave spectrum with a medium frequency in a range from 125 to 2000 Hz and for heavy sources in a spectrum from 63 to 500Hz. So-called grade curves (Fig. 2) are used for evaluations of single numbers. Sorting into classes is governed by the condition that the determining grade curve given must not be exceeded by more than 2dB. If this is the case, then the ceiling structure is categorized into a lower class.

2.4.2 Evaluation of the performance of floor impact sound insulation of buildings using an inverse A characteristic curve

An interesting form of single-number assessment is the procedure defined in Annex 3 of JIS 1419-2. This procedure is marked as a reference. Similar to the procedure above, this form of evaluation can be applied to both light and heavy excitation sources. A single number quantity is expressed in dB from a full octave band. When focusing on the heavy/soft source, the spectrum in the range from 63 to 500Hz is evaluated (Fig. 3). For the evaluation, the so-called inverse A-weighted standard curve is used, which is shifted in 1dB steps so that the sum of the difference in exceeding the reference curve by the measured spectrum must not be more than 8dB. The single number value is determined from the value of the reference curve at 500Hz. In cases of heavy sources, the single number expression is denoted by the subscript H(1) or H(2), depending on whether a bang machine or a rubber ball was used ($L_{iA,Fmax,AW,H(1)}$ or $L_{iA,Fmax,AW,H(2)}$).

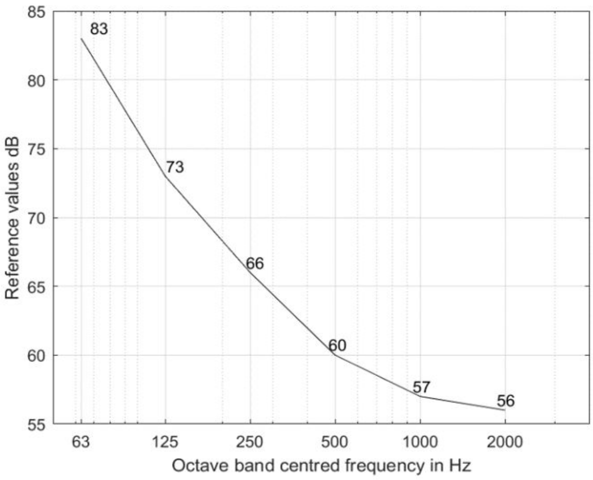

Fig. 3 *Inverse A-weighted standard curve in accordance with JIS A 1419-2 (JIS, 2019)*

2.5 Determination of SNQ in accordance with KS F 2863-2

Despite the great similarity of the procedures mentioned in the JIS and KS standards in connection with heavy/soft impact sources, the KS F 2863-2 standard leans somewhat more towards the procedures preferred by ISO in 2022 (Kim et al., 2023). Specifically, the previous ”Bang machine” excitation source was replaced by a rubber ball. The single number rating corresponds to the procedure according to the inverse reference curve described above.

2.6 SNQ Requirements

In order to provide a comprehensive overview, we are also presenting a short summary of requirements for impact noise generated by heavy sources. As stated in (Hiramitsu, 2024), there is no legislation in Japan setting out the requirements for the performance of ceiling construction impact noise. Therefore, they often refer to the standards of the Architectural Institute of Japan (AIJ, 1997). The classification of ceiling structures excited by a heavy/soft source (Bang machine) into the classes defined herein distinguishes 4 different classes. It recognizes Special Grade (L_{r-45}), First Grade (L_{r-50}), Second Grade (L_{r-55}), and Third Grade (L_{r-60} and L_{r-65} - for timber construction only). The required value for ceilings in residential houses in Korea must not exceed the value of 49dB. Currently, requirements in dwelling houses are classified into four grades (grade 1: $L \leq 37$; grade 2: $37 < L \leq 41$; grade 3: $41 < L \leq 45$; and grade 4: $45 < L \leq 49$).

3 METHODS

In order to compare the single-number evaluation procedures recommended by the ISO, JIS, and KS respective standards, a set of numerically generated noise level spectra was created. A total of 8400 spectra were subsequently evaluated for individual SNQs. $Li_{A,Fmax}$ and $L_{i,FmaxAV;}$ $Li_{A,Fmax}$, and L_{i-xx}; $Li_{A,Fmax}$ and $Li,_{FmaxAV}$ were compared. As in the last two cases, the SNQ determined as an approximate value of the sound energy in the receiving room was compared with two evaluation variants using reference curves. In these cases we did not focus on the effect of the equivalent absorption area of the receiving room on the measured values. The comparisons were relative. However, for the first case of the comparison, we also focused on the effect of the change in the room volume (constant reverberation time T=0.5s and a variation in the room volume from 25 to 400m3) or the average sound absorption in the receiving room (a room volume constant of V =50m^3, and the reverberation time ranged from 0.1 to 3.6s).

3.1 Numerically generated spectra

In order to cover as precisely as possible the entire frequency and dynamic range of commonly recorded values, whether in a laboratory environment or in the field, a set of two packages of spectra (a total of 8400 curves) was numerically created based on the internally obtained measurement data of $L_{i,Fmax}$. The first group of curves can generally be characterized by the function $f(x)=1/(1+e^{-x})$, which has been shifted on the horizontal (x-axis). The dynamic variation in the vertical direction (y-axis) was in a range from 20 to 110dB (Fig. 4). The second group of curves was created based on the function sin(x), for x={0,π}. In this case, the dynamic range was focused on a range from 0 to 80dB (Fig. 4).

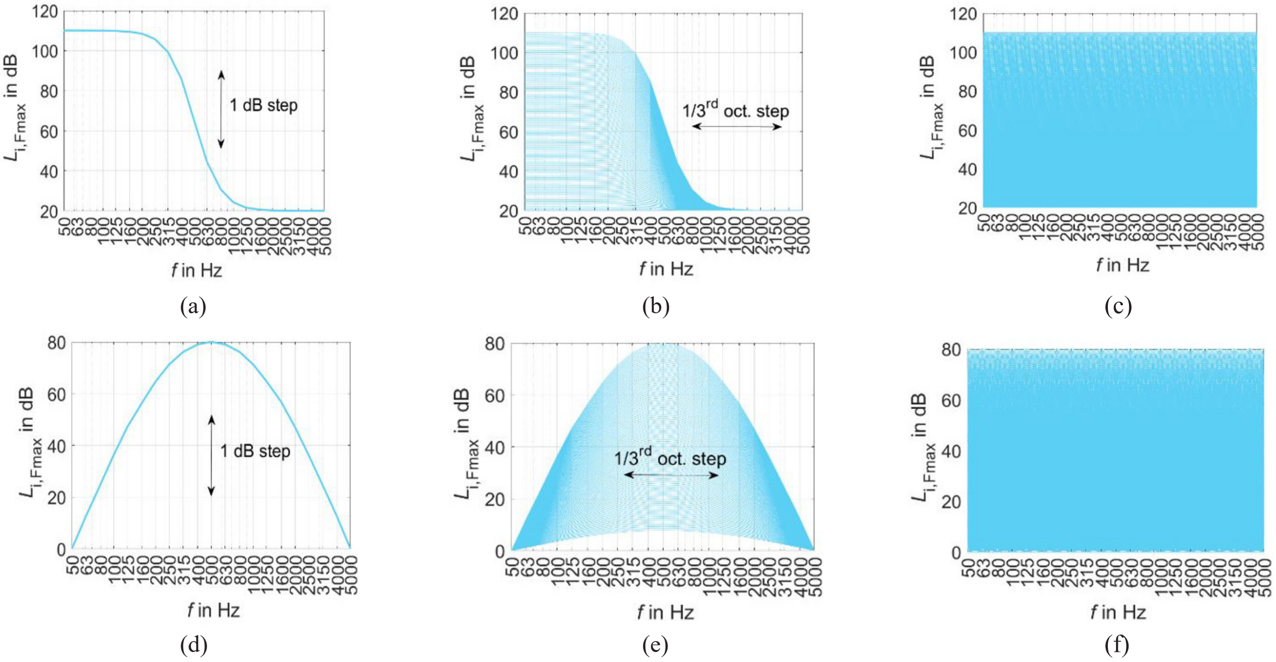

Fig. 4 *Scheme of the $L_{i,Fmax}$ spectra generation. a,d) basic function; b,e) multiple attenuation of the basic function; c,f) multiple shifts of the function*

4 FINDINGS AND ARGUMENTS

In this part, the results of the comparison of the individual methods of the single number evaluation are presented according to the procedure explained in the previous section. As expected the correlation between $L_{iA,Fmax}$ and $L_{iA,Fmax,V,T}$ is linear (Fig. 5). Since the reference volume of the receiving room was V_0=50m^3 and the reference reverberation time in the receiving room was T_0 =0.5s, the values $L_{iA,Fmax}$ and $L_{iA,Fmax,V,T}$ were equal as expected for these boundary conditions. By doubling the volume of the receiving room with a constant reverberation time, $L_{iA,Fmax,V,T}$ increased by 3dB and vice versa (Fig. 5a). The effect of the reverberation time variations with the constant volume of the receiving room (50m^3) can be expressed by the function $\Delta L_x(T) = 0.004041\cdot T^4 - 0.1024\cdot T^3 + 0.9856\cdot T^2 - 4.749\cdot T + 9.395$. In the case presented in (Fig. 5b), the effect of doubling the reverberation time makes a shift in $L_{iA,Fmax}$ and $L_{iA,Fmax,V,T}$ in a range of 1.4 to 2.5dB. For the L_{i-xx} ranking-based grade curves, the correlation is affected by the fact that the grade or reference curves are in step with 5dB (Fig.6). When classifying the individual spectrum into classes, the frequency position of its maximum or the possible peak of the spectrum is decisive. Therefore, there is a wide dispersion of correlation data in this parametric study at the level of the individual grades (in the lower grades, it is up to 15dB). Thanks to the use of a relatively extensive package of spectra for this parametric study, another phenomenon was recognized. By plotting the envelope over all the spectra belonging to one class, we get a curve corresponding to the reference curve of this determining method itself (Fig.7).

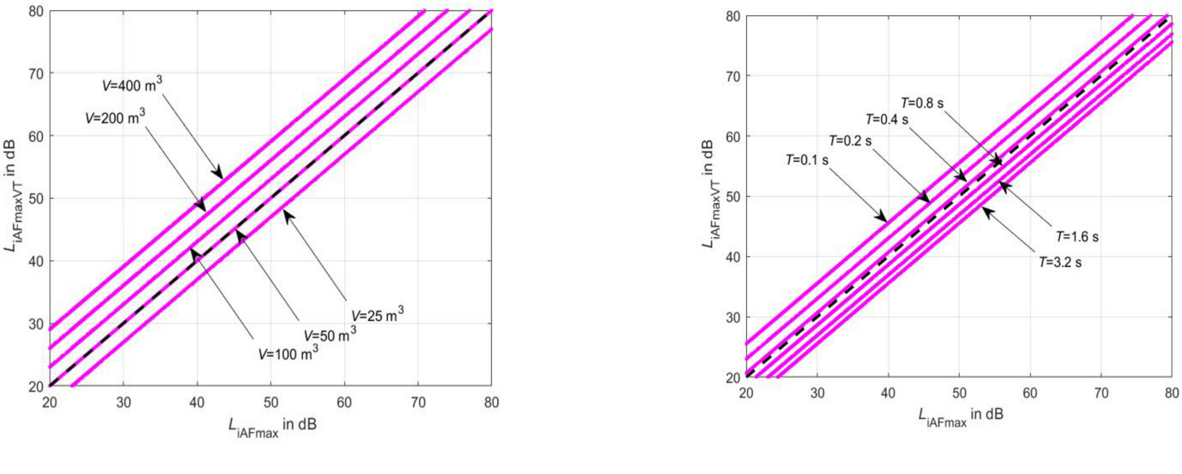

Fig.5 *Correlation between LiA,Fmax and Li,FmaxAV expressed for: a) Receiving room volume variation with a constant T=0.5s ; b) Receiving reverberation time variation with a constant volume V =50 m^3*

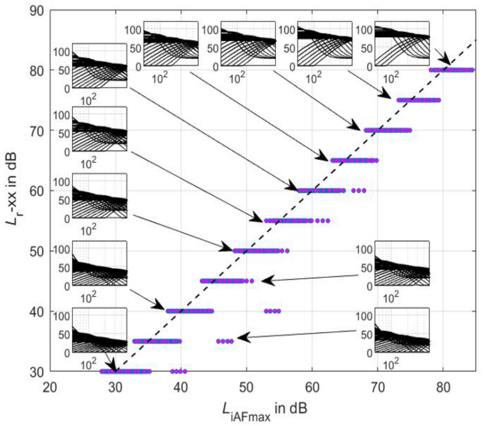

Fig.6 *Correlation between the $L_{iA,Fmax}$ and $L_{i\text{-}xx}$ single number rating. In the small windows, the noise level spectra are presented in a range from 63 to 500Hz falling into the individual grades ($L_{r\text{-}30}$ to $L_{r\text{-}80}$).*

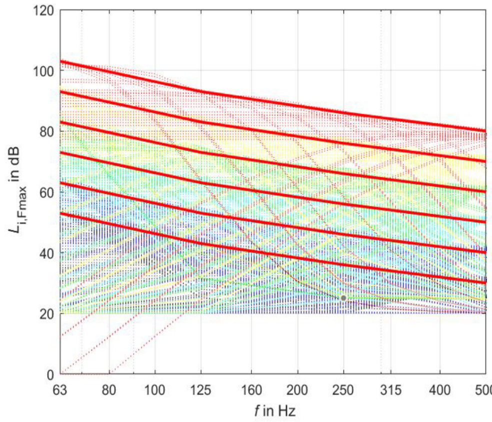

Fig. 7 *Graphic representation of the envelope of the individual spectra of the parametric study according to the grades*

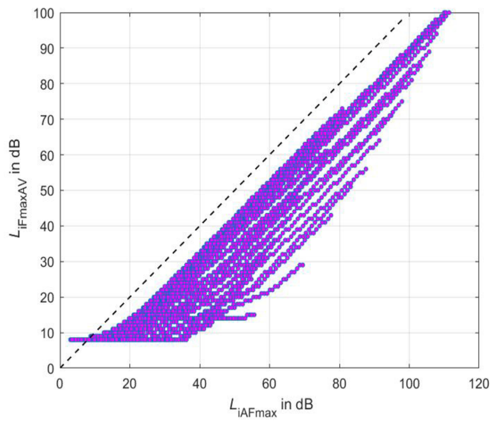

Fig. 8 *Correlation between the $L_{iA,Fmax}$ and $L_{iFmaxAV}$ single number rating.Red - rubber ball; Black - bang machine.*

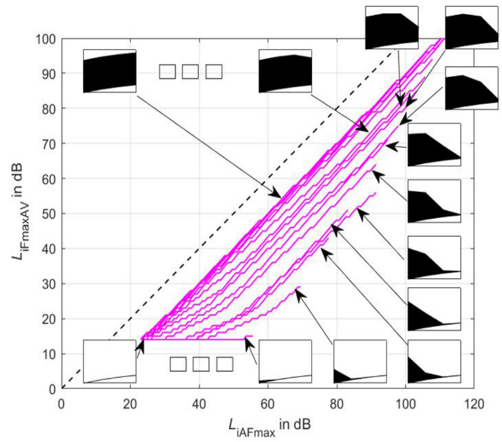

Fig. 9 *Correlation between the $L_{iA,Fmax}$ and $L_{iFmaxAV}$ single number rating. In the small windows, the noise level spectra characterized by the function $f(x)=1/(1+e^{-x})$ are presented in a range from 63 to 500Hz, falling into individual curves (slopes)*

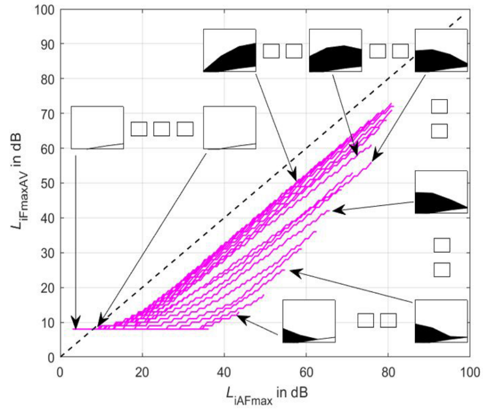

Fig. 10 *ICorrelation between the $L_{iA,Fmax}$ and $L_{iFmaxAV}$ single number rating. In the small windows, the noise level spectra characterized by the function sin(x) are presented in a range from 63 to 500Hz falling into individual curves (slopes)*

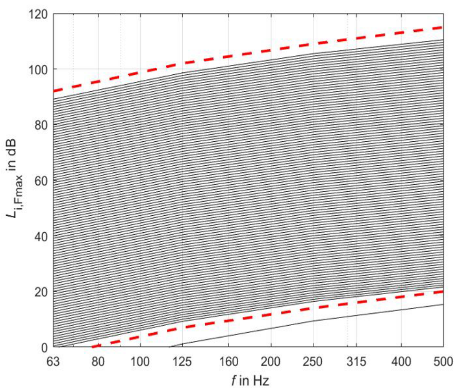

Fig. 11 *Noise level spectra characterized by the function $f(x)=1/(1+e^{-x})$ presented in a range from 63 to 500Hz falling into a linear correlated curve with a shift of 7dB for $L_{iA,Fmax}$ and $L_{iFmaxAV.}$ The dashed red curves indicate the inverse shape of the reference curve randomly shifted in a y-axis direction.*

In the case of curves defined by the function f(x)=1/(1+e-x), the linear correlation of the single number values can be partially observed in the case of the shape of the spectra inverse to the reference curve (Fig.11). A less intuitive dependency applies to the other shapes and the function sin(x)-based spectra generated.

5. CONCLUSION

Both today's practice and research on building acoustics force us to think about the issue of low-frequency noise the generated by walking in residential and public buildings. In addition to a focus on the uncertainty of the measurements and the correlation of subjective tests with the usual objective methods of evaluating ceiling structures, we need to think about the possibilities of introducing single-number requirements on the international level for excitation by heavy/soft sources. Despite the fact that the ISO standard provides a procedure for determining the maximum level of impact noise, there are no building acoustic requirements for excitation with heavy/soft standardized sources in Europe. A total of four approaches to a single number rating based on LA,Fmax for a frequency band from 50 to 630Hz were compared in this contribution. In the case of ISO-defined procedures, a linear deviation has been observed, which is solely related to the volume of the receiving room and its reverberation time. The comparison of the ISO and JIS evaluations has shown the dependence of the results on the shape of the spectrum of the noise. This is caused by the use of different reference curves in the JIS and KS evaluation procedures, as opposed to those in the ISO standards. The proposed ISO single number ranking provides higher values in general.

In both evaluation methods based on reference curves, specific cases of linear correlation were recognized. However, those were minor cases. In spite of the fact that several studies focusing on a comparison of the subjective evaluation of the constructions stimulated by a tapping machine and rubber ball have already been carried out (Jeon et al., 2006, Vardaxis and Bard, 2018, Vorländer, 2020, Andargie et al., 2023, Park and Lee, 2017), there is still no internationally harmonized single number rating procedure that correlates with the perception of a barefoot walk in households, which is currently the most common way. That is probably also the reason why there is no internationally harmonized procedure based on reference curves yet for heavy/soft excitation sources. Therefore, it is desirable to deal with this issue in the future. In further work, involvement of the perception-based subjective testing with a statistically significantly relevant number of persons tested will be essential.

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