AKUSTICKÉ LISTY

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ročník 27, číslo 1–4 prosinec 2024

Contents

ČESKÁ AKUSTICKÁ SPOLEČNOST

Akustické listy, **27**(1–4), prosinec 2024, str. 3–6

Nonlinear Distortion of Microphone in Probe for Otoacoustic Emission Measurements

Nelineární zkreslení mikrofonu v sondě pro měření otoakustických emisí

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Nonlinearities in otoacoustic emission (OAE) measurement probes can significantly impact the accuracy of distortion-product otoacoustic emissions (DPOAE) results. This paper investigates the nonlinear behavior of condenser microphones used in these probes. Due to the lack of a perfectly linear reference source, we employ harmonic correction methods found in the literature to address the nonlinearities. We measure the second and third harmonics produced by the microphone, estimate key parameters of the nonlinear microphone model from these measurements, and use this model to predict the nonlinear behavior of the microphone in two different measurement scenarios. In the first scenario, without a low-frequency bias tone, the nonlinear distortion produced by the microphone is negligible. In the second scenario, with a low-frequency bias tone, the nonlinear distortion becomes significant. The findings demonstrate that we are able to measure the microphone's nonlinearities and estimate key model parameters to predict the significance of these nonlinearities in different measurement scenarios.

1. Introduction

Otoacoustic emissions (OAEs) are sound signals generated within the inner ear and transmitted across the middle ear to the external ear canal [1]. It can be used for diagnosing hearing impairments. These emissions can be spontaneous, but diagnostic methods are based on measuring OAEs evoked by an external stimulus. In clinical practice, the method of measuring distortion-product otoacoustic emissions (DPOAE) [2] is commonly used. DPOAEs are distortion products generated in the inner ear in response to a stimulus with two spectral components at closely spaced frequencies, f_1 and f_2 ($f_1 < f_2$). The primary distortion product monitored with this method is the cubic intermodulation product at the frequency $2f_1 - f_2$ [3]. From the above, it is evident that any nonlinearity in the electroacoustic measurement chain can affect the results.

The otoacoustic emission measurement probe typically contains two miniature loudspeakers (each of the two spectral components is generated separately to reduce the effect of intermodulation distortion on the speaker). To capture the response to the measuring signal, the probe also contains a miniature condenser microphone with a flat frequency response and low inherent noise. The probe is connected to the external ear canal via a small tube. In this work, we focus on measuring nonlinearities of the microphone in the OAE probe.

One of the main challenges in accurately measuring nonlinearities in microphones is the lack of a perfectly linear reference source of acoustic signal, which complicates the measurement process by making it difficult to distinguish between nonlinearities produced by the microphone and those produced by the source. To address this, a harmonic correction method is employed for periodic signals [4]. This method uses predistortion to reduce the nonlinear effects of the acoustic source to the background noise level using a reference microphone with negligible distortion, allowing measurement of only the nonlinearities created by the microphone under test.

In the following sections, we provide a theoretical background on condenser microphone nonlinearities, and present the details of the measurement setup. Finally, we discuss the measured results and use of the theoretical model for understanding the microphone's behavior under two different measurement scenarios.

2. Theoretical model of nonlinearities in condenser microphones

Nonlinearities in condenser microphones can arise from various factors, such as changes in capacitance due to varying electrode distances, nonlinear damping, and mechanical or electronic components [5, 6]. The electrostatic transduction mechanism is the main source of distortion in condenser microphones, producing both harmonic and intermodulation distortion [7, 8]. The second harmonic alone accounts for about 90 % of the total harmonic distortion according to [9]. These effects become particularly prominent at high sound pressure levels.

The theoretical model of nonlinearities in condenser microphones, based on the analysis in [10], is presented here. The model focuses on the electrostatic transduction mechanism, assuming other sources of nonlinearities are

Přijato 1. listopadu 2024, akceptováno 15. ledna 2025.

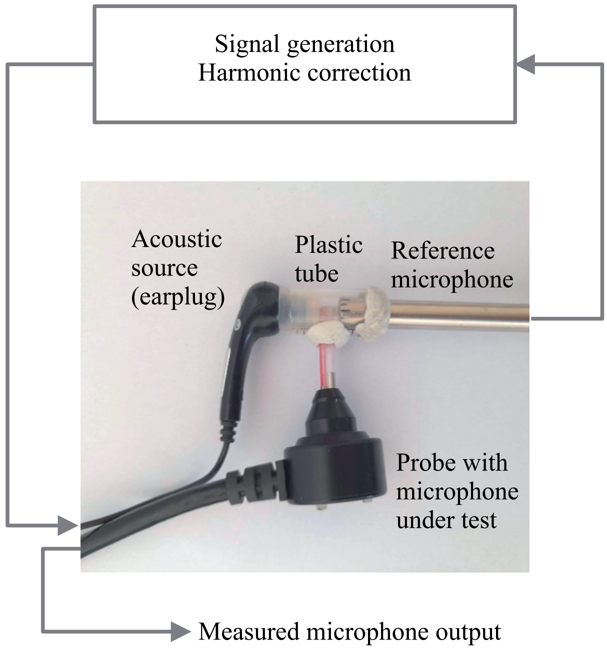

Figure 1: Measurement setup

negligible. The output voltage, assuming negligible charge change due to a high polarizing resistor, is given by

$$u(t) = -U_0 \frac{\mathrm{d}C(t)}{C}, \tag{1}$$

where U_0 is polarization voltage, $\mathrm{d}C(t)$ is the capacitance change, and C is the total static capacitance of the microphone.

The total capacitance $C(t)$ is given by

$$C(t) = C_\mathrm{p} + \frac{\varepsilon_0 S}{h_\mathrm{g} + \bar{\xi}(t)},$$

where $\bar{\xi}(t)$ is the mean displacement of the membrane, h_g is the thickness of the air gap between the membrane and the fixed electrode, S is the surface of the fixed electrode, and ε_0 is the permittivity of the vacuum. Assuming that the total capacitance $C(t)$ is composed of parasitic capacitance C_p, static active capacitance C_0, and capacitance change $\mathrm{d}C(t)$, i.e., $C(t) = C_\mathrm{p} + C_0 + \mathrm{d}C(t)$, the capacitance change can be simplified using a Taylor series to

$$\mathrm{d}C(t) = -C_0 \left[\frac{\bar{\xi}(t)}{h_\mathrm{g}} - \left(\frac{\bar{\xi}(t)}{h_\mathrm{g}} \right)^2 + \left(\frac{\bar{\xi}(t)}{h_\mathrm{g}} \right)^3 - \cdots \right]. \tag{2}$$

Substituting (2) to (1) and denoting $y(t) = \bar{\xi}(t)/h_g$ the relative mean membrane displacement to the air gap thickness and $K_0 = U_0 \cdot C_0/(C_\mathrm{p} + C_0)$, the voltage at the output of the microphone can be rewritten as

$$u(t) = K_0 \left[y(t) - y^2(t) + y^3(t) - \cdots \right], \tag{3}$$

where the nonlinear components are clearly visible. Single key parameter K_0 has to be estimated from the measurements.

3. Measurements and results

The measurement setup consists of a probe with a low-noise condenser microphone, the reference microphone and the acoustic source, see Fig. 1. The probe used in this study is the Etymotic ER10C, which includes two low-noise microphones whose outputs are summed to reduce distortion and improve accuracy, with a sensitivity of 50 mV/Pa. The probe is designed to operate without significant distortion up to 120 dB SPL. The reference microphone is a standard laboratory 1/4″ measurement microphone B&K 4135, and the acoustic source is an earplug. Both microphones and the source are inserted into a plastic tube, forming a small cavity to achieve high acoustic pressures, see Fig. 1.

Using the same measurement procedure as in [10], the first (fundamental), the second and the third harmonic of the microphone under test output voltage were measured. Figure 3 shows these harmonics, recalculated to the acoustic pressure levels measured by the microphone under test through its known sensitivity (points), along with the theoretical results (dashed lines) calculated using eq. (3) and estimated value of $K_0 = 48\,\mathrm{V}$ (see [10] for details). There is good agreement between the theoretical and measured results for the first and second harmonics, irrespective of frequency. Minor discrepancies can be attributed to the non-flat frequency response of the microphone under test, leading to slight variations in sensitivity across frequencies. The measured level of the third harmonic is significantly higher than the predicted value, consistent with previous measurements [10], indicating the influence of nonlinear effects in the microphone that are not accounted for in the simplified model used in this study.

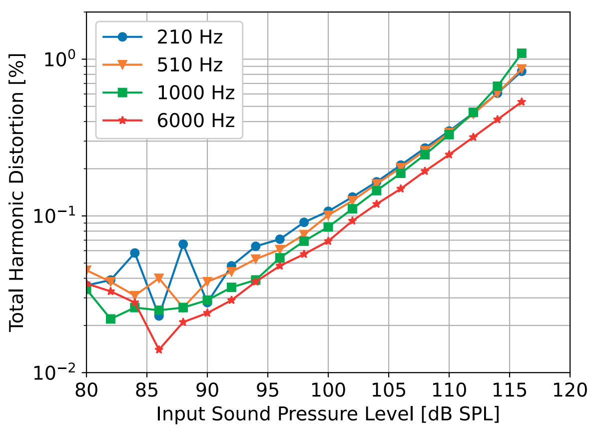

Figure 2: Measured Total Harmonic Distortion (THD) vs. input acoustic pressure level at different frequencies

Figure 2 presents a Total Harmonic Distortion (THD) as a function of the input acoustic pressure level, calculated from the previously mentioned results. The findings confirm that nonlinear distortion in condenser microphones remains relatively consistent across frequencies. At 6000 Hz, the THD is slightly lower compared to other frequencies, likely due to a reduced third harmonic component. It should be noted that values below 90 dB SPL are significantly affected by background noise.

4. Prediction of microphone behavior for two measurement scenarios

With the key parameter of the microphone's nonlinear model, K_0, estimated from the measurements presented in the previous section, we can now theoretically analyze the nonlinear behavior of the microphone under two different measurement scenarios.

The first scenario involves a typical DPOAE measurement using two harmonic components, specifically at 1000 Hz and 1200 Hz. Figure 4 shows the theoretical spectra: (i) the acoustic pressure at the input of the microphone (thick line) and (ii) the acoustic pressure virtually measured by the probe microphone, calculated using the nonlinear microphone model (eq. (3)) with the estimated parameter K_0.

At an input level of 70 dB SPL for both components, the intermodulation products caused by microphone nonlinearities remain below −15 dB SPL, which is within the range of the typical noise floor observed in DPOAE measurements (0 to −20 dB SPL, depending on frequency) [3]. This finding confirms that the nonlinear behavior of the probe microphone is negligible for this type of measurement.

The second scenario involves a measurement with three harmonic components: two components similar to those used in a typical two-component DPOAE measurement, and an additional low-frequency component of relatively high amplitude. This method, proposed in the literature [11, 12, 13, 14], is used to provide a bias to the operating point of the cochlear transducer. In this study, we maintain the 1000 Hz and 1200 Hz components at the level of 70 dB SPL, while adding a low-frequency component at 100 Hz with a level of 100 dB SPL, as shown in Fig. 5. The simulation results indicate that the second harmonic of the low-frequency component approaches 40 dB SPL, and the intermodulation products at 900 Hz and 1300 Hz reach 15 dB SPL. These levels are not negligible and may influence the results of DPOAE measurements.

5. Conclusion

The study demonstrated that it is possible to measure the nonlinear distortion in microphones used in otoacoustic emission probes. In most practical cases, the distortion is insignificant, but under specific conditions, the second harmonic component becomes a critical factor. Future work will explore compensating for these distortions to improve measurement accuracy.

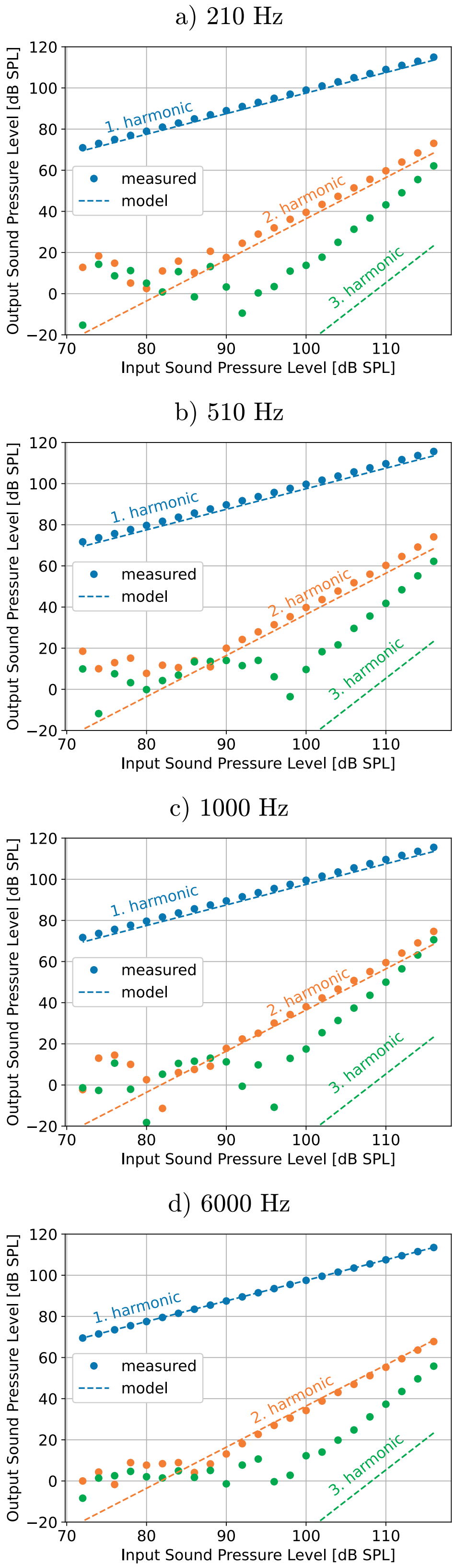

Figure 3: Measured (points) and theoretical (dashed lines) harmonics of the microphone under test at a) 210 Hz, b) 510 Hz, c) 1000 Hz, and d) 6000 Hz

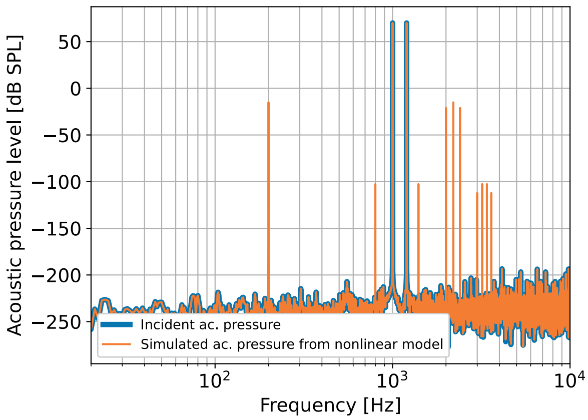

Figure 4: Theoretical spectra of the incident acoustic pressure (thick line) and of the acoustic pressure given by the nonlinear microphone model (thin line) for the 2-component measurement scenario

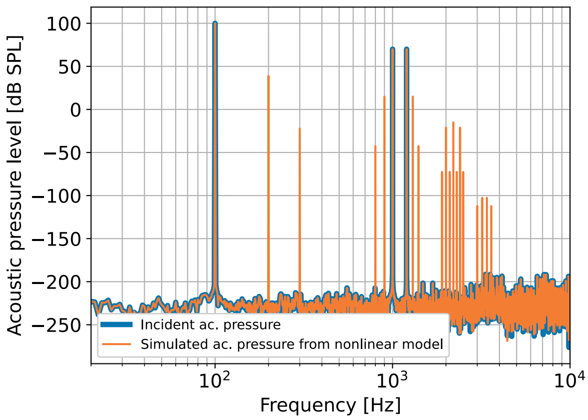

Figure 5: Theoretical spectra of the incident acoustic pressure (thick line) and of the acoustic pressure given by the nonlinear microphone model (thin line) for the 3-component measurement scenario

Acknowledgment

This work was supported by the project 23-07621J of the Czech Science Foundation (GAČR) “Otoacoustic emissions in normal cochlea and cochlea with endolymphatic hydrops: modeling and experiments”.

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Spatial Ambience and Mediated Sound in Connected Remote Spaces

Charakter a mediace dozvuku u distančně spojených prostor

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Spatial ambience and reverberation present important qualities of perceived sound and are relevant for mediated audio in common and musical interactions over remote connections. Several conditions, such as the coupled state of the connected spaces and temporal lag of the transmission, might be proposed as influential to their character. This research aims to document the influence of both conditions using acoustic measures and evaluated room ambience. The results support the conclusion that both the coupling and temporal lag can influence reverberation in the connected state and increase the reverberance in the room. The effect of latency on room ambience is observed to be negative and is also discussed as distinct relative to those described in previous studies.

1. Introduction

An increasing proportion of personal interactions occurs over remote connections and using mediated sound. Scenarios of these connections can be diverse, but most include a connection of actual spaces using transduced and streamed audio, and some might even aim for an aesthetic purpose or include musical content and even interaction of performers [1].

An audio signal and reproduced sound can be influenced at all stages of the transmission chain and during its capture and reproduction in the connected locations. Such influence can have audible effects on the ambience[1] of the mediated sound in both locations and might also influence the acoustics and reverberation in both spaces.

Reverberation and its ambience can have qualitative significance for the character of the perceived sound and can also be relevant for other concepts such as immersion [2, 3]. The presence and character of reverberation during a musical interaction can influence the intonation, dynamics, timbre and support of performers [4, 5]. Reverberation can also be of particular concern in small rooms, as these present common locations of remote interactions and features of their acoustics might lead to a negative relation of their reverberation to the perceived sound [6, 7, 8, 9].

Connected spaces are coupled through the transmission chain and the chain has been described to act as their coupling aperture. Dual reverberation slopes have been observed in coupled rooms of differing sizes [10], but additional outcomes can also be anticipated for small rooms or connection latency. The latter presents a popular subject of remote interaction studies, but its acoustic effects can present a further outcome in its common range[2] [11]. Microphone position is of similar interest as it can mediate ambience and also alters the aperture.

This research therefore aimed to observe the consequences of such circumstances. These include increased reverberation in the connected spaces due to the coupling of similar rooms and its further increase due to the connection latency. Similar effects could also be observed for other parameters including the ratio of *early* and *late* energy and perceived ambience. These are therefore studied in this research.

2. Methods

The research uses data from acoustic measurements made in a subset of connected spaces used for remote practice and ratings of room ambience gathered from participants of such practice. Both originated in a pair of unrelated studies.

The acoustic measurements constitute of measured sinetone responses in 3 rooms for each unique combination of induced states (1 original state of each room and 8 combinations of its interconnections to 2 other rooms in 2 states of transducer distance and 2 latencies). The measured states include 0 and 50 ms latencies (induced using a DSP in the interface) and 1m and 2m distances of the transducers (a change of the position of a speaker in the measured room and microphone in the distant room along the line of their alignment to induce the state of microphone to speaker distance in both rooms). Sizes and labels of the rooms are presented in Table 1.

Table 1: Rooms and their dimensions [m]

	1			2			3		
Sizes	3.5	5.0	3.2	4.5	5.5	3.2	5.0	6.0	3.2

[1]Ambience: *the character of a place* or *quality given to a recorded sound by a space*. Reverberation: *a repercussion* or *prolongation of a sound* [12]

[2]Latencies of ~ 50 ms

Přijato 16. září 2024, akceptováno 27. prosince 2024.

The audio chain consisted of an aligned set of a single speaker and cardioid microphone (Genelec 1029A and Røde NT5[3]) at on both ends of the connection. Its setup copied its usual setup in the rooms[4]. Conversion of the audio signal and its routing occurred on a RME Fireface 802 over AES3 and had sub 1/2 ms input-output latency. All audio and measurement elements cleared the room boundaries by 1 m.

The room responses are measured using e-sweep sine tones generated in DIRAC (Brüel and Kjær). The tones were reproduced using an omnidirectional 4292 sound source placed 1 m ahead of the broadcast microphone and received using an omnidirectional 4006 microphone 1 m diagonally to the side of the source at 3 positions of the source and receiver (equidistant positions of the source in a 20° incidence range to the broadcast microphone). Procedures in DIRAC are used for computing the reverse integrals and C_{80} and T_{30} metrics from the recorded responses in the bands in Table 1. The results from the responses in each triplet of positions are averaged as repeated measurements.

Conclusions based on objective parameters complement those on subjective ratings form observational research at the authors' institution. It covered remote musical activities of 21 student or masterclass participants, in a single room and on a similar repertoire (accompanied singing) and identical audio setup (identical to the one described above), but on diverse streaming tools (MVTP-audio or a PC [13]). Participants on the local side reflected each session using questionnaires and rated its *items audiovisual qualities*, *synchrony* and *room ambience* (*please rate the perceived character of the room*) on an impression scale[5]. Corresponding latencies present their measurements noted to the nearest 10 ms, in intervals labeled at their outer range to prevent bias due to their distribution.

All of the parameters above are used as indicators of the investigated qualities. C_{80} represents a log ratio of the first (early) and remaining (late) sound energies in room response (indicating the presence useful or resonant reflections) and the T_{30} represents a diffuse slope of reverberation (indicating reverberance). Both metrics have subjective relevance [14]. Subjective ratings of room character are used to indicate the qualities of room ambience.

3. Analysis

The C_{80} and T_{30} metrics for the measurement triplets are used as single cases of observed data. Their numbers in each band are then averaged into groups of similar bands in Table 2 (for groups having been identified as commutable according to the results of hierarchical clustering and principal component analyses [PCA]) and are used in further analyses. Statistics of correlation coefficients of the reverse integrals and predictions of the T_{30} regression lines are also used to inspect the fitness and linearity of the slopes.

A linear multilevel model for each of the metrics is used to determine the difference of estimated means for each studied condition. Difference of the means relative to the initial state of the room (Table 3) or of both latencies (Table 4) is used as indicator of the influence of the conditions and the associated factors. Its significance is tested using Bonferroni adjusted F-tests. Intercept of the individual rooms is modeled as random effect in the model (random intercept) and the tables therefore present the results for all rooms. An additional multiple linear regression model using the latencies and all-band averages of initial states of both metrics in the remote and local room as their predictors in the connected state is further developed in Table 6.

Similar tests are also used to analyse the subjective ratings of *room character* after filtering the ratings for cases having reported timing problems (filtering out scores below 0 for *synchrony*). Percentiles of the ratings in the 2 represented ranges of latencies are used to describe the distributions and a linear F-test and Mann-Whitney tests are performed to test for their difference (Table 5).

4. Results

Results of the PCA and clustering analyses of C_{80} and T_{30} data are presented in Table 2: the factors and their loadings and the mean distances for each closest pair suggest the bands in the 2 factors and 3 clusters are commutable and could be reduced to single groups. The correlation coefficients near 1 in all bands[6] and suggest a linear nature of the T_{30} slopes.

Table 2: Octave bands and factor loadings of the metrics, their clusters, closest pair distances and the grouping

Band	Factor	Loading T_{30}	Loading C_{80}	Cluster	Distance	Group
125	1	.76	.91	1	0.022	125
250	1	.93	.95	1	0.022	
500	1	.62	.82	1	0.027	
1000	2	.87	.85	2	0.013	1000
2000	2	.92	.90	2	0.013	
4000	2	.97	.93	3	0.003	4000
8000	2	.96	.96	3	0.003	

The fine structure of the T_{30} data is presented in detail in Figure 1. The graph presents a distribution of the T_{30} values in the rooms in their connected states at 0 ms and 50 ms latencies and the original state of the room labeled as initial in the graph. The rooms are rendered as blue (1) amber (2) and green (3) and the consecutive band groups as displaced plots. Dotted lines connect the means for each room (coloured) and a global mean (black). The

[3] 20 dB 1 kHz back attenuation

[4] Lossless 96/24 bit audio and −6 dB end to end gain at 1 m

[5] −5 – *considerably worse*, 0 – *usual*, 5 – *considerably better*

[6] 0.999 (0.99 outer bound)

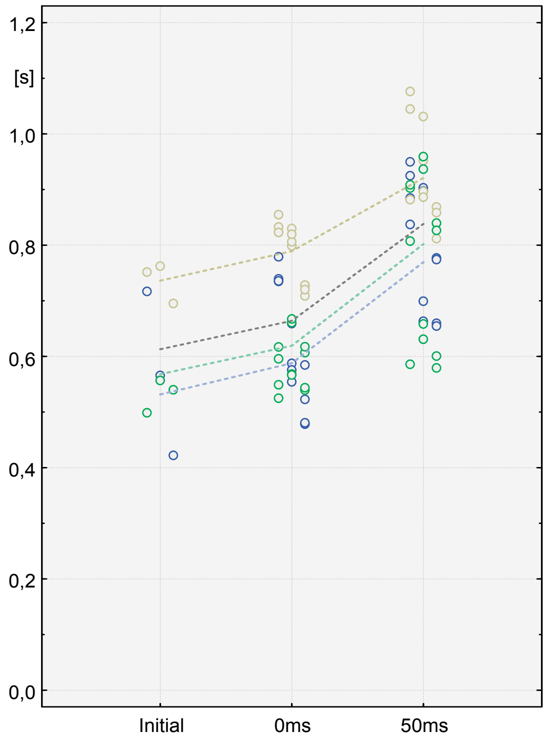

Figure 1: T_{30} distribution in each room (coloured), octave band group (offset) and condition. Lines connect the means for each room (coloured) or a global mean (black)

distributions are different in different rooms and at different frequencies but their mean increases uniformly in all rooms and grouped bands.

The differences of the estimated means for all parameters and settings and their significance might be inspected in Table 3. The results indicate that the effects of the transducer distance[7] are minor but are pronounced for latency.

Table 3: Differences of estimated means and F-test for each condition, indicator and group

Condit.	Ind.	Group	Diff.	F	Sig.
Latency	C_{80}	125	0.81	12.6	**
		1000	0.98	31.3	***
		4000	1.86	27.2	***
	T_{30}	125	−0.18	42.7	***
		1000	−0.17	53.6	***
		4000	−0.15	90.4	***
Distance	C_{80}	125	−0.28	1.5	
		1000	−0.23	1.7	
		4000	−0.29	0.6	
	T_{30}	125	0.02	0.5	
		1000	0.00	0.0	
		4000	0.00	0.1	

[7] C_{80} change at 2 m relative to 1 m is small and insignificant

The differences of estimated means for the unconnected and connected rooms at 0 and 50 ms latencies and the F-tests of the difference are presented for each parameter and octave band group in Table 4. The tests indicate that the presence of the connection and the associated coupling affects C_{80} and T_{30} in isolation but that the difference further increases for C_{80} and almost doubles for T_{30} at the higher latencies.

Table 4: Differences of estimated means relative to the unconnected room and F-test for each indicator and group

State	Ind.	Group	Diff.	Sig.
0 ms	C_{80}	125	1.17	**
		1000	1.48	**
		4000	2.34	*
	T_{30}	125	−0.16	***
		1000	−0.13	**
		4000	−0.13	***
50 ms	C_{80}	125	1.43	***
		1000	1.86	***
		4000	3.13	***
	T_{30}	125	−0.24	***
		1000	−0.21	***
		4000	−0.20	***

The descriptives and statistical test results for the ratings of room ambience from actual remote practice are presented in Table 5. Percentiles for the room character ratings detail the distribution of the ratings and indicate their increased negative dispersion in the higher relative to the lower range of latencies. Both statistical tests of the difference are in agreement and significant and confirm the difference of ratings amid both groups. Sign of the difference of the least square means is negative and documents an average trend in the direction of decreased ratings on increasing latency.

Table 5: The ratings of ambience: percentiles and difference tests (F-test, difference of means, Mann-Whitney U)

ms	Percentile			Test statistic				
	F_{10}	F_{25}	F_{75}	Diff.	F	Sig.	U	Sig.
50	−2	−1	0	−0.67	7.01	**	255	**
0	0	0	0					

The results of the additional regression using the latencies and measured initial states the metrics in remote and local room as their predictor in the connected states are presented in Table 6. It is apparent from the results that the resulting C_{80} and T_{30} in the connected rooms matches a linear function of the C_{80} and T_{30} in each of the connected rooms and the factor of latency. The standardized beta coefficients in Table 7 hint on the relative contribution of latency to both parameters. Its contribution to T_{30} is considerable, and is higher than that of the

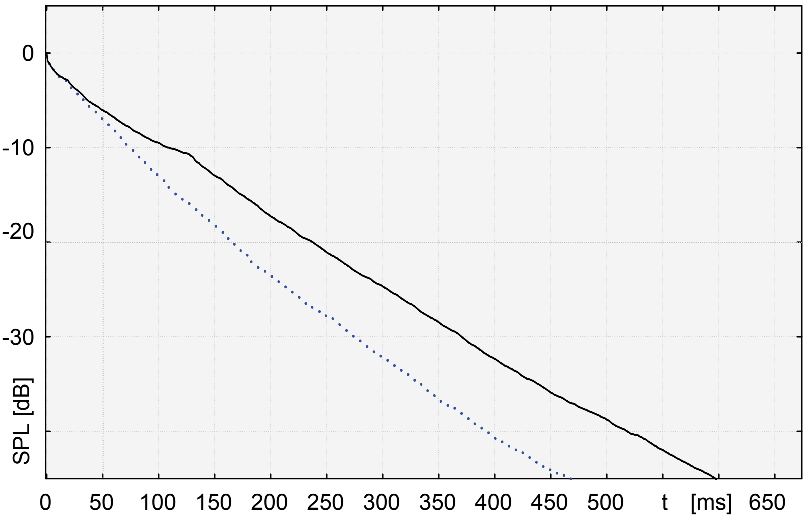

Figure 2: The reverberation slope integrals for a single pair of connected rooms at 0 ms (blue dotted) and 50 ms (black solid) latency

remote room, and its contribution to C_{80} presents a significant portion of its overall change. The high fit of both functions is also substantial.

Table 6: The fit of the linear regression (R^2, Adj. R^2) and its significance (F, Sig.)

	R^2	Adj. R^2	F	Sig.
C_{80}	.96	.95	154.3	***
T_{30}	.89	.88	56.4	***

Table 7: The B and beta coefficients for the predictors for both T_{30} and C_{80} parameters

	Predictor	B	Beta	Sig.
C_{80}	Latency	−2.17	−0.24	***
	Local	2.07	1.09	***
	Remote	0.95	0.42	***
T_{30}	Latency	0.17	0.63	***
	Local	1.20	0.81	***
	Remote	0.68	0.46	***

An illustration of the reverberation slopes in the first room and a single measurement position is presented in Figure 2 at the end of this article. A single notch corresponding to the returned reflections can be seen at the higher latencies. It is rather smeared for an echo and does not appear repeatedly. Its described form further supports the conclusion that indirect attenuated reflections in the room dominate the feedback and change of ambience.

5. Discussion and conclusion

The results demonstrate that a presence of electroacoustic connection in remote rooms can influence the reverberation in the rooms. Size of the observed effects is comparable to those due to audience and occupants or other conditions factored in acoustic design [15]. Its causes include the aspect of coupling of the connected rooms and transmission chain latency. The influence of both aspects demonstrates itself as an increase in the level and duration of a late[8] and general reverberant energy.

The acoustic effects are distinct relative to those described in related studies, as the reverberation slopes are logarithmic relative to the ones described for coupled rooms of different sizes [10], and their mechanism concerns perceived spatial qualities and acoustics, rather than timing and its cognitive consequences [16]. The results therefore increase the range of documented acoustic effects of the coupling to small rooms and an aspect of its latency.

A relation of the perceived ambience in the room and both studied conditions can be observed for the temporal aspect in the ratings from remote practice, and can also be implied for both measured parameters from their reported or established qualitative relations or difference limen in studies [6, 7, 17]. Both might be used in a conclusion that the influence is audible and can be negative. Similar conditions and settings occur in actual activities [11, 18] and so might be relevant qualitatively. Common forms of their mediation could further impair the sound or induce further latency, and might present topics for further research[9].

Changing the distance of elements acting as aperture in the audio chain and their location relative to boundaries of the room did not have a significant effect on either of the metrics. Minute and insignificant results observed for the ratio of the first and late energies could relate to the interaction of directional components in the sound field [19] and directional response of the transducers, and might

[8] > 80 ms

[9] Such as de-reverberation, transducer response and mediating techniques

hint at a possible relation of the effects to the later diffuse reflections. Onset of the returning reflections from the remote room at higher latencies is also gradual and does not seem to have a sudden or repeating character such as that of a flutter echo. Similar reflections are recognised to cause the Larsen effect in high gain public address loops [20] but the effects observed here present their further and distinct consequence in an additional scenario and invite consecutive research and parametric or modeling studies.

Practical suggestions might include those on the need to better recognise the influence of diverse latencies and room designs on perceived ambience during the remote sessions and on the relative irrelevance of the far field microphone to speaker distance in its management.

Although the studied musical scenario could be the most fitting for the observed effects, the measurements and ratings document a general effect in the studied spaces that might relate to other forms of qualitative remote interactions or even other domains, such as the design of conference rooms or live monitoring.

Acknowledgements

This article has been supported as part of a project titled *Research of relevant aspects for directing sound and music in remote performances* by a specific university research grant provided to the Academy of the Performing Arts in Prague in 2023 by the Ministry of Education, Youth and Sports of the Czech Republic

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Akustické listy, **27**(1–4), prosinec 2024, str. 13–20

Effect of Floor Finishing Materials on Impact Sound Pressure Level

Vliv finálních nášlapných vrstev na hladinu kročejového zvuku

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In this paper, it is demonstrated by experimental measurement how the floor finishing material may affect the final values of normalized impact sound pressure level by adding different floor finishing materials to a typical floating floor system. The experiment was conducted for a residential building under construction with finished subfloors and floor finishing materials laid upon them. Field experimental measurements were performed according to technical standards ČSN EN ISO 717-2 and ČSN EN ISO 16283-2 in the sound insulation frequency range 100–3150 Hz, but also frequencies below 100 Hz (range between 50 and 100 Hz) were considered. As shown by the results, the adding of a floor finishing material usually has a positive effect on impact sound pressure level in the mid and high frequency range. This outcome was expected, but also it is obvious that the use of a vinyl flooring or a carpet as a floor finishing material is more effective in the attenuation of impact sound pressure level than the use of a laminate flooring or floor tiling. Moreover, the experimental measurement proved that the amplification of impact sound pressure level on lower frequencies is an issue in many cases unavoidable with present knowledge and technology.

1. Introduction

Impact sound insulation is one of two types of sound insulation which are commonly observed in residential buildings. Its value is represented by the quantity called normalized impact sound pressure level L'_{n} (dB). The final quantity, which is compared with the requirement of Czech technical standards ČSN 73 0532, is called weighted normalized impact sound pressure level $L'_{\mathrm{n,w}}$ (dB) and is always measured in situ. Its compliance is obligatory and has to be ≤ 53 dB in residential buildings [1].

From the acoustic point of view, the main influence in reducing the transmission of impact sound is the use of a suitable floating floor system. Buildings often remain unfinished during proving measurements of the impact sound insulation. More precisely, subfloors are completed, but no floor finishing materials have yet been installed, due to the different demands of future flat users. If a measurement made under conditions matches the requirements of ČSN 73 0532, it is usually accepted that a subsequently added floor finishing material will not worsen the result, but conversely, could also improve the situation [2]. This also assumes Seunguk et al. [3].

Branco et al. [4] tested the behaviour of a slab after the use of a floating wood floor or ceramic tiles and stated that the presence of the underlay has a dominant influence on the global performance of the system. Similar measurements were conducted by Arenas and Sepulveda with laminate flooring [5]. However, it needs to be mentioned that everything depends on the specific performance of each floor finishing material, because in a few cases (as this paper will prove) the outcome may be even worse.

Moreover, computer technology often fails to take floor finishing materials into consideration and their added effect is often calculated only by the experience of the designer him-self. Prediction models are difficult to set up [2, 6]. Accordingly, the specific type of floor finishing material tends to be ignored and an additional measurement is not required, though its effect is not negligible as it may differ from flat to flat. Mun et al. [7] conducted an experimental study using 14 PVC floor coverings and 16 floor mats to capture the characteristics of impact noise in residential buildings. The softer the finishing materials, the greater decrease was observed in im-pact sound pressure levels.

Therefore, it is worth investigating whether the impact of different floor finishing materials (which are shown in Table 1 – Mun et al. [7] tested in general only two materials) is significant or not (and additionally, in comparison with the others).

Table 1: The floor finishing materials used

Measurement	
No. 1	see Figure 1
No. 2	+ laminate flooring 8 mm
No. 3	+ Mirelon 3 mm + laminate flooring 8 mm
No. 4	+ 2× Mirelon + laminate flooring 8 mm
No. 5	+ other underlay + laminate flooring 8 mm
No. 6	+ Mirelon 3 mm + vinyl flooring 5 mm
No. 7	+ other underlay + vinyl flooring 5 mm
No. 8	+ carpet 8 mm
No. 9	+ floor tiling 10 mm

Přijato 12. září 2022, akceptováno 6. dubna 2023.

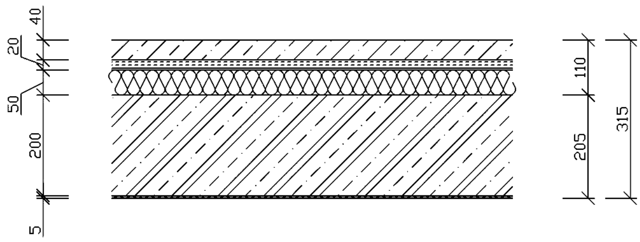

Figure 1: Configuration of a measured floating floor system

2. Measurement conditions and process

The experimental measurement took place in a residential building which was under construction. Its structural system was a load-bearing wall system which consisted of concrete slabs and masonry walls. Two living rooms with an identical ceiling configuration were chosen for field measurements. The configuration of the floating floor system is shown in Figure 1: atop a concrete slab (200 mm) lies expanded polystyrene EPS (50 mm) and above it are a resilient material (20 mm) and anhydrite screed (40 mm).

In total, 9 field measurements were conducted, of which the first one was performed on the subfloor (shown in Figure 1), while the others substituted various floor finishing materials laid on the subfloor (anhydrite screed). A list of used materials is shown in Table 1. Measurement No. 3 is illustrated by a photograph in Figure 2.

Measurements No. 2 to No. 8 were always performed with a small sample of each floor finishing material. The objectivity of these measurements could be questioned, as the materials were not firmly attached to the anhydrite screed, but the technical standard ČSN EN ISO 16283-2 (as the active standard for all the measurements) allows this method when small samples of floor finishing materials are shifted from one position to another within the room. This sample should have an area of at least $1\,\mathrm{m}^2$. Areas of all used samples ranged only up to $2\,\mathrm{m}^2$. This method needs to be mentioned in a protocol, because results could be misleading, as discussed before [8].

Figure 2: Example of measurement No. 3

Therefore, the test results of these measurements serve only to provide information about the added effect of floor finishing materials on the final values of transmission of impact sound, because ČSN 73 0532 forbids this method in proving the obligatory requirement, which is ≤ 53 dB in residential buildings [1].

Measurement No. 9 was performed in a living room that was below the first one considered. In this room, the floor tiling was already finished and firmly attached to the anhydrite screed in the whole area. Other conditions were kept constant, hence this structure (without the floor tiling) should provide identical properties to the one in Measurement No. 1. A bar chart is attached at the end in Figure 4. This chart draws a comparison between reverberation time measurements for both living rooms. Standard deviations show that results of reverberation time relatively varied in the low frequency range. The volume of both rooms was $V = 92.86\,\mathrm{m}^3$ and $V = 90.77\,\mathrm{m}^3$. ČSN EN ISO 16283-2 determines that a low-frequency method must be used in the case of rooms with volume lower than $25\,\mathrm{m}^3$, which is not this case [8].

To simulate the impact sound noise, a tapping machine was selected as a source – shown also in Figure 2. The source was always applied in the source room at four points following ČSN EN ISO 16283-2. In the receiving room, a microphone was utilized for measuring the impact sound pressure levels – always in four positions for each position of the tapping machine. The background noise was also recorded to consider its possible influence. A flare gun was used for discovering the reverberation time of the examined living rooms.

Afterwards, measurements were evaluated according to technical standards ČSN EN ISO 717-2 in the sound insulation frequency range 100–3150 Hz. In addition, frequencies below 100 Hz (50, 63 and 80 Hz) were considered, though they do not contribute to the final value of the weighted normalized impact sound pressure level $L'_{\mathrm{n,w}}$ (dB). However, to understand the behaviour of each of the floor finishing materials used, values of normalized impact sound pressure level L'_{n} (dB) at frequencies of 50 to 100 Hz are noteworthy, as this range is always crucial in subjective perception of impact sound.

Moreover, it is proven that a floating floor is not effective in reducing impact sound pressure levels in the low frequency range. In most cases, impact sound pressure levels below 63 Hz frequency band were actually increased by the resonance of a resilient material, a subfloor, and a floor finishing material [9].

In addition, the spectrum adaption terms C_{I} (dB) and $C_{\mathrm{I,50–2500}}$ (dB) have been determined.

Specifically, the floor finishing materials used were:

- laminate flooring – Egger Pro Classic 32 (oak Olchon honey EPL144), thickness 8 mm,

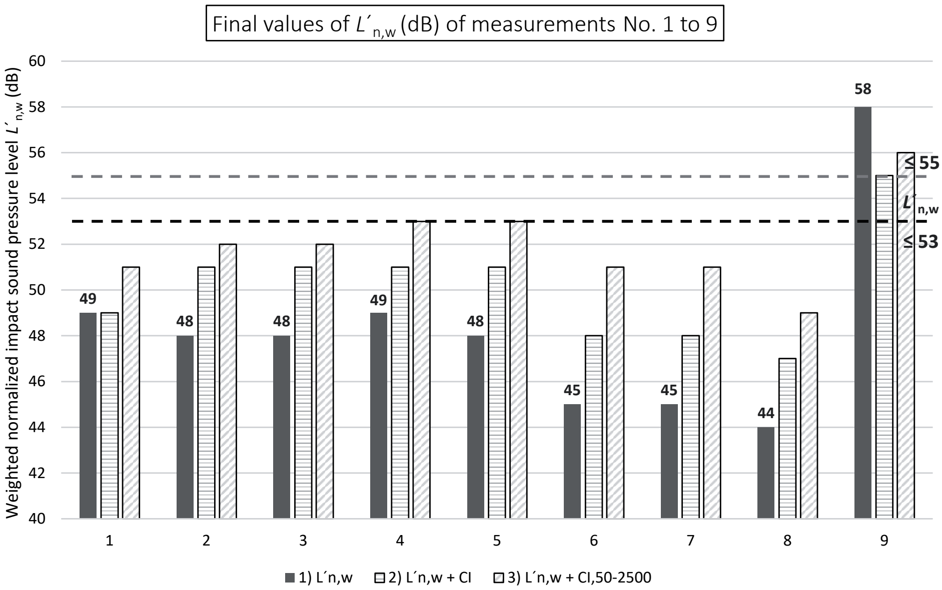

Figure 3: Comparison between weighted normalized impact sound pressure level $L'_{\mathrm{n,w}}$ (dB) of all conducted measurements

- another underlay – Arbiton Secura MAX Aquastop Smart 3in1, thickness 5 mm,
- vinyl flooring – Pergo (Grey Scottish Oak), thickness 5 mm
- carpet – Primavera type 153, pile height 4 mm, total thickness 8 mm,
- floor tiling – RAKO Extra, cat. number: DAR63723, thickness 10 mm.

3. Measurement results

Measurement No. 1 is considered as a referential – meaning that the other conducted measurements are related to this one and the values of normalized impact sound pressure level L'_{n}(dB) are compared with those from the first measurement to investigate whether (and where) impact sound pressure levels increased or decreased. Generally, the levels were assumed to be better (lower) due to the positive effect of the floor finishing material [2]. As shown by the results, this statement was correct except for the last (ninth) measurement with the floor tiling, where all values increased in the whole range of 50 to 3150 Hz. The comparison between the final values of the weighted normalized impact sound pressure level $L'_{\mathrm{n,w}}$ (dB) is in Figure 3; the comparison between evaluated normalized impact sound pressure level L'_{n} (dB) values is in Figure 5 and their specific numerals are in Table 2 at the end of this paper.

All these measurements fulfilled requirement $\leq$ 53 dB (or $\leq$ 55 dB dB, which was valid at the time the buildings construction permit was issued), with only the last one unfortunately failing to meet the terms of ČSN 73 0532. Other measurements met conditions with sufficient safety. The basic configuration of the ceiling (measurement No. 1 – without floor finishing materials) may be considered as satisfying ($L'_{\mathrm{n,w}}$ = 49 dB). However, in contrast to the other measurements, it can be seen that past the frequency greater than 250 Hz, the transmission of impact sound is higher. This transmission has little influence on the value of the weighted normalized impact sound pressure level, but still its impact may be more than negligible for the future flat users who could sense this transmission as disturbing. After the laying of a floor finishing material on the anhydrite screed, this issue disappears, because this floor finishing material has a positive effect on the impact sound pressure level in the mid and high frequency range, typically above 400 Hz (here except for the floor tiling) [10].

Within the low frequency range, the sound pressure level is slightly increased in general (especially with laminate flooring), except for the carpet flooring. This phenomenon occurs mostly at the spectrum adaption term $C_{\mathrm{I},50\text{–}2500}$ (dB), whose value increases with increasing impact sound pressure level at low frequencies. Though the value of weighted normalized impact sound pressure level is decreasing (which is positive), this issue at low frequencies may have a negative impact on subjective perception of the impact sound. With present knowledge and technology, this amplification is often unavoidable, because resonant frequency is increased by these floor finishing materials.

One interesting finding is in the use of laminate flooring, when the value of the weighted normalized impact sound pressure level $L'_{\mathrm{n,w}}$ decreased from 49 dB only to 48 dB, but from Figure 5, it is visible that after the adding of an underlay – Mirelon, thickness 3 mm (measurement No. 3) or Arbiton Secura, thickness 5 mm (measurement No. 5) – there is a significant attenuation of the sound pressure level at frequencies greater than 800 Hz, which had also a positive effect on the observers perception of the impact sound during the measuring in the receiving room. This proves the suitability of underlays that are laid under many floor finishing materials to decrease the transmission of impact sound.

Also, it is obvious that the use of vinyl flooring (measurement No. 6 and 7) or carpet (measurement No. 8) as a floor finishing material is more effective in the attenuation of the impact sound pressure level than the use of the previous laminate flooring within the whole sound insulation range of 100 to 3150 Hz. As such, the weighted value decreased from 48 dB (No. 2) to 45 dB or 44 dB. The explanation is simple – these two materials are softer (better dynamic stiffness) than laminate flooring and reduce impulses of the tapping machine and following transmission of impact sound noise from the very beginning, causing its limited creation [2, 11].

To sum things up, the best possible floor finishing material leading to the most significant attenuation of the impact sound in this experimental field measurement is carpet, closely followed by vinyl flooring. However, it should be noted that this effect may not invariably be the same in every situation. Another factor is the pile height of the carpet and its total height, but still in general it is more likely that the addition of carpet flooring would never worsen the situation, even when firmly attached [2].

The last measurement, No. 9, never met the requirement $\leq$ 53 dB (or even $\leq$ 55 dB) and the course in Figure 5 indicates that amplification was present within the whole sound insulation frequency range. The use of floor tiling is always hazardous, because there is a risk that even a slight rigid interconnection between ceramic floor tiles and flanking structures may lead to a dramatic increase of the normalized impact sound pressure level L'_{n} (dB) through the forming of an acoustic bridge, which also occurred here. This issue was also shown by Karl Gösele (1964) in a laboratory experiment [2].

In addition, Figure 6 contains a graph representing the change of the normalized impact sound pressure level L'_{n} (dB) of all measurements Nos. 2 to 9, relative to the first referential (in which no floor finishing material was installed upon the anhydrite screed). The figures for these changes are displayed in Table 3 in the end of this paper.

4. Conclusion

In addition to the results presented in chapter 3, other outcomes could be possible.

If there is any issue after the construction of the subfloors with the increased transmission of impact sound at lower frequencies (50 to 200 Hz), the adding of any floor finishing material (except for certain types of carpet flooring) will not improve the situation (see Figure 5 and 6). The attenuation of the normalized impact sound pressure level L'_{n} (dB) will appear in the mid and high frequency range, but these are not the crucial frequencies in this specific case, nor will there be significant improvement in the weighted value. Either way, the range of lower frequencies will not be solved, but also in fact could be even worsened. The issue of the increased transmission of impact sound at lower frequencies happens because of imperfect elastic interconnections around the floor perimeter [2], an unsuitable resilient material or its insufficient thickness, leading to higher dynamic stiffness which causes the resonance frequency to increase [2, 5, 11]. That means that the construction solution (and its good performance) is the most important issue within the lower frequency range.

The measurement also showed that (for example) the use of laminate flooring may improve the value of the weighted normalized impact sound pressure level $L'_{\mathrm{n,w}}$, but a problem could exist of increased transmission of impact sound at lower frequencies [5].

The last measurement (No. 9) proved that if there is a dramatic increase of impact sound pressure level at the lower frequency range, it often indicates a rigid interconnection through which the impact sound is transmitted.

Nevertheless, it needs to be mentioned that all the used samples of floor finishing materials (except for measurement No. 9) were not firmly attached to the anhydrite screed, so the results of this experiment might perform less well if they were indeed firmly attached.

Acknowledgment

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS 24/004/OHK1/1T/11.

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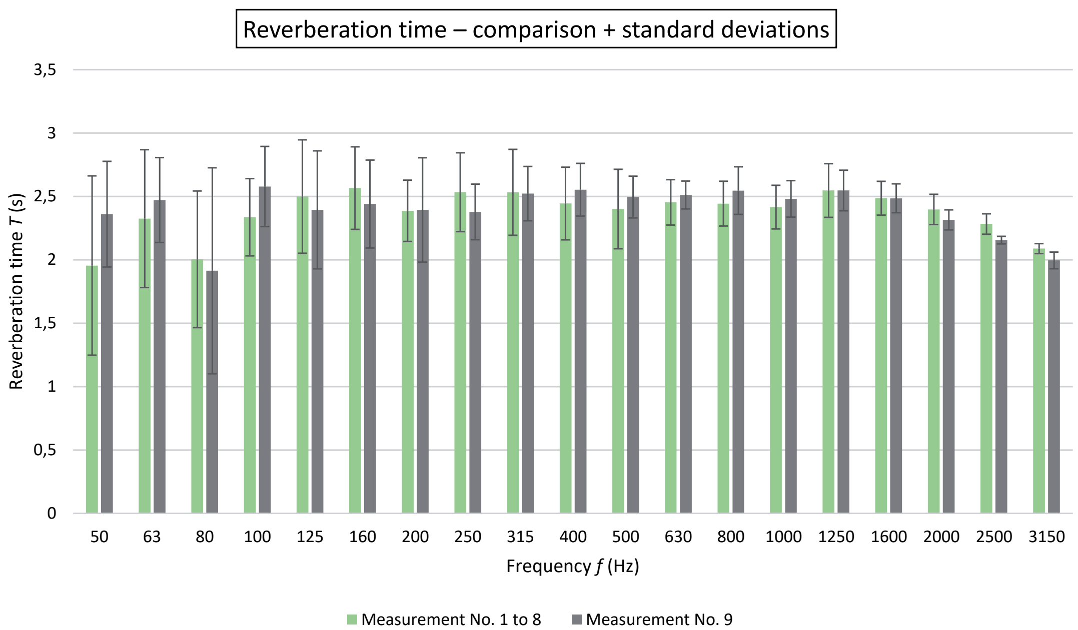

Figure 4: Comparison of reverberation time between two living rooms including standard deviations

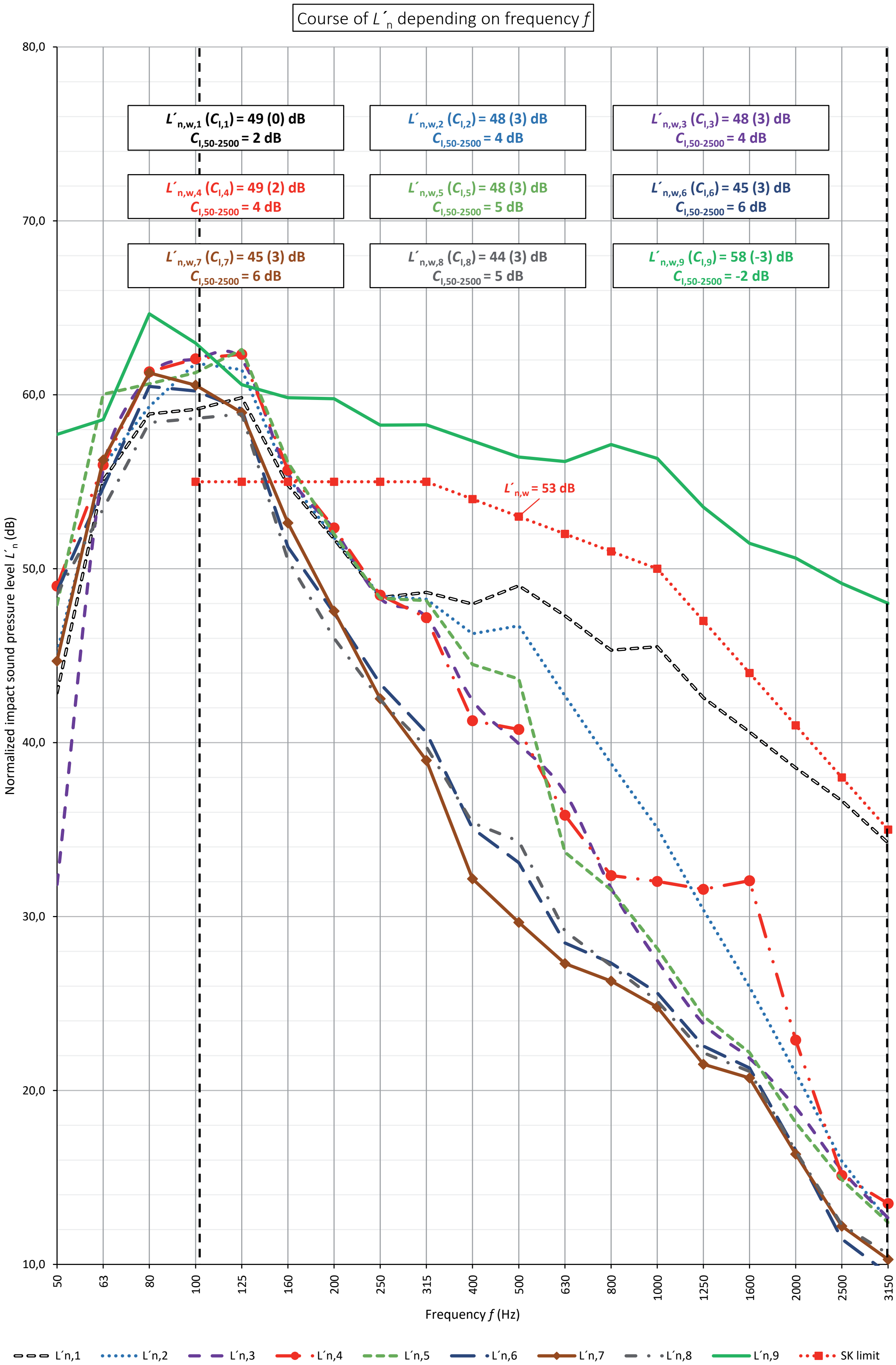

Figure 5: Normalized impact sound pressure level L'_n (dB) of all conducted measurements

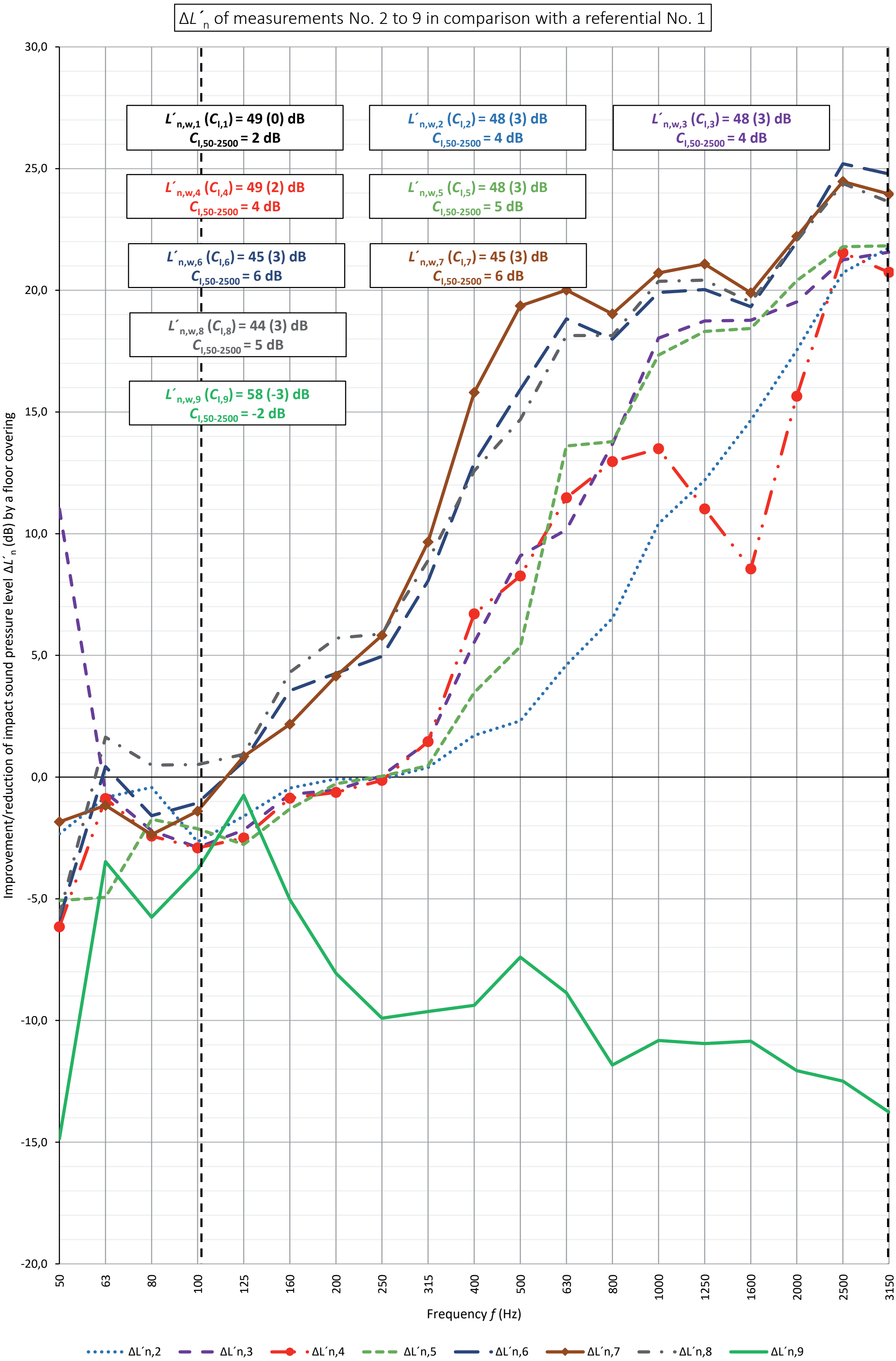

Figure 6: Improvement/reduction of impact sound pressure level $\Delta L'_n$ (dB) by a floor covering

Table 2: Evaluated values of normalized impact sound pressure level L'_n (dB)

f (Hz)	$L'_{n,1}$ (dB)	$L'_{n,2}$ (dB)	$L'_{n,3}$ (dB)	$L'_{n,4}$ (dB)	$L'_{n,5}$ (dB)	$L'_{n,6}$ (dB)	$L'_{n,7}$ (dB)	$L'_{n,8}$ (dB)	$L'_{n,9}$ (dB)
50	42,9	45,2	31,8	49,0	47,9	48,7	44,7	48,5	57,7
63	55,1	55,9	55,7	56,0	60,0	54,7	56,3	53,4	58,6
80	58,9	59,3	61,1	61,3	60,6	60,5	61,3	58,4	64,7
100	59,2	61,8	62,1	62,1	61,3	60,2	60,6	58,6	63,0
125	59,8	61,4	62,0	62,3	62,6	59,2	59,0	58,9	60,6
160	54,8	55,3	55,5	55,7	56,1	51,3	52,6	50,5	59,8
200	51,7	51,8	52,2	52,3	52,0	47,5	47,6	46,0	59,8
250	48,3	48,4	48,3	48,5	48,3	43,4	42,5	42,5	58,3
315	48,6	48,2	47,2	47,2	48,2	40,6	39,0	39,7	58,3
400	48,0	46,3	42,4	41,3	44,5	35,1	32,2	35,4	57,3
500	49,0	46,7	39,9	40,8	43,7	33,1	29,7	34,3	56,4
630	47,3	42,7	37,1	35,8	33,7	28,5	27,3	29,2	56,2
800	45,3	38,8	31,6	32,4	31,5	27,3	26,3	27,2	57,1
1000	45,5	35,1	27,5	32,0	28,2	25,6	24,8	25,1	56,3
1250	42,6	30,4	23,8	31,6	24,3	22,6	21,5	22,2	53,5
1600	40,6	26,0	21,8	32,1	22,2	21,3	20,7	21,1	51,5
2000	38,5	21,0	19,0	22,9	18,2	16,6	16,3	16,5	50,6
2500	36,7	15,9	15,4	15,1	14,9	11,5	12,2	12,3	49,2
3150	34,2	12,5	12,7	13,5	12,4	9,5	10,3	10,6	48,0
$L'_{n,w}$ (dB)	49	48	48	49	48	45	45	44	58
$C_{I,100–3150}$ (dB)	0	3	3	2	3	3	3	3	−3
$C_{I,50–2500}$ (dB)	2	4	4	4	5	6	6	5	−2

Table 3: Evaluated values of an improvement/reduction of impact sound pressure level $\Delta L'_n$ (dB)

f (Hz)	$\Delta L'_{n,2}$ (dB)	$\Delta L'_{n,3}$ (dB)	$\Delta L'_{n,4}$ (dB)	$\Delta L'_{n,5}$ (dB)	$\Delta L'_{n,6}$ (dB)	$\Delta L'_{n,7}$ (dB)	$\Delta L'_{n,8}$ (dB)	$\Delta L'_{n,9}$ (dB)
50	−2,3	11,0	−6,1	−5,1	−5,8	−1,8	−5,7	−11,9
63	−0,8	−0,6	−0,9	−4,9	0,4	−1,2	1,6	−3,5
80	−0,4	−2,2	−2,4	−1,7	−1,6	−2,4	0,5	−5,8
100	−2,7	−2,9	−2,9	−2,1	−1,1	−1,4	0,5	−3,8
125	−1,6	−2,2	−2,5	−2,8	0,6	0,9	0,9	−0,7
160	−0,4	−0,7	−0,9	−1,3	3,5	2,2	4,3	−5,0
200	−0,1	−0,5	−0,6	−0,3	4,3	4,1	5,7	−8,1
250	−0,1	0,1	−0,1	0,0	5,0	5,8	5,9	−9,9
315	0,4	1,4	1,5	0,5	8,1	9,7	8,9	−9,6
400	1,7	5,5	6,7	3,5	12,9	15,8	12,6	−9,4
500	2,3	9,1	8,3	5,4	15,9	19,4	14,7	−7,4
630	4,6	10,2	11,5	13,6	18,8	20,0	18,1	−8,9
800	6,5	13,7	13,0	13,8	18,0	19,0	18,1	−11,8
1000	10,4	18,0	13,5	17,3	19,9	20,7	20,4	−10,8
1250	12,2	18,7	11,0	18,3	20,0	21,1	20,4	−11,0
1600	14,7	18,8	8,6	18,4	19,3	19,9	19,5	−10,8
2000	17,5	19,5	15,7	20,4	22,0	22,2	22,0	−12,1
2500	20,7	21,2	21,5	21,8	25,2	24,5	24,4	−12,5
3150	21,7	21,6	20,7	21,8	24,8	24,0	23,6	−13,8

Akustické listy: ročník 27, číslo 1–4 prosinec 2024 ISSN: 1212-4702
Vydavatel: Česká akustická společnost, z. s., Technická 2, 166 27 Praha 6
Počet stran: 24 Počet výtisků: 200

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Uzávěrka příštího čísla Akustických listů je 31. října 2025.