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Research Paper

Issues in the Design and Validation of Coupled Reverberation Rooms for Testing Acoustic Insulation of Building Partitions

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The paper presents the characteristics of the sound field in two pairs of coupled reverberation rooms, designed in accordance with International Organization for Standardization [ISO] (2021c). The analyses are based on the results of the following studies. Firstly, the acoustic airborne sound insulation of selected test samples was measured in the reverberation rooms without using any sound diffusing nor sound absorbing elements. In the second step, the tests were repeated successively with an increasing number of diffusers installed in the rooms. The last stage of the research involved measurements with additional absorbers mounted in the rooms. The results show that although the geometry and construction of the reverberation rooms are in line with the standard guidelines, in most situations it was necessary to use diffusing and absorbing elements to improve the acoustic field in the rooms. Such elements, however, are very undesirable as they significantly limit the usable space of the rooms, making it more difficult to assemble samples and distribute sources and measurement points in the measurement space. Later in the article, the authors prove that even using typically available design tools, i.e., 1st and 2nd Bonello criterions, numerical simulations with the image-source method and the finite element method, or more advanced research methods, such as measurements using scaled samples, it seems impossible to prevent at the design stage the future necessity of using additional diffusing and absorbing elements in the reverberation rooms. Only via verification by measurements performed in the completed rooms provides the assessment if such additional elements are required.

Keywords: reverberation chambers; transmission loss; acoustic field; small scale model.

1. Introduction

The test bench for measuring the airborne sounds insulation of building partitions consists of two coupled reverberation rooms (according to (ISO, 2021a)). In order to achieve adequate repeatability and reproducibility of measurements (based on (ISO, 2014)), the test stand must follow strict guidelines. These guidelines are applicable to the geometry and construction of the reverberation rooms described in (ISO, 2021c) as well as to the measurement equipment and procedure described in (ISO, 2021b). While the requirements for the selection of appropriate equipment and the implementation of the correct measurement procedure are precise and unambiguous, the guidelines for the construction and, in particular, the geometry of the reverberation rooms are very general (they relate only to the volume of the rooms and the area of the measurement window). Therefore, coupled reverberation rooms in various laboratories may be constructed differently (for example: (Uris *et al.*, 2007; Zhu, 2022; Oliazadeh *et al.*, 2022)). As a consequence, the distribution of the sound field in these rooms and its influence on the measurement results will also vary as shown in (Dijckmans, Vermeir, 2013). According to (ISO, 2021c), the sound field in reverberation rooms should be as diffused as possible. If sufficient sound diffusion is not ensured by the interior geometry alone, additional diffusing elements are required. To quote the standard: "the position and number of diffusing elements should be arranged in such a way that the sound reduction index is not influenced when further diffusion elements are installed" (ISO, 2021c, p. 2). However, at the design stage, it is difficult to accurately model the acoustic field inside the reverberation rooms which was studied by Chazot *et al.* (2016), Schmal *et al.* (2021) or Bork (2000), let alone its effect on the measurement results. In practice, the qualification procedure is carried out only after the rooms have been constructed. For qualification, sound diffusers (Zhu, 2022; Bradley *et al.*, 2014; Mleczko, Wszołek, 2019) as well as sound absorbing elements (Fuchs *et al.*, 2000; Yao *et al.*, 2020) are installed in the rooms to unify the sound field inside. Unfortunately, such measures involve additional costs and also obstruct work in the laboratory until the rooms are adapted for testing. Furthermore, additional sound absorbing and diffusing elements significantly limit the usable space of the rooms, making it more difficult to assemble samples and distribute sources and measurement points in the measurement space.

This paper presents the characteristics of the sound field in two pairs of coupled reverberation rooms, designed following the guidelines and the requirements of (ISO, 2021c). The need for additional design guidelines to achieve satisfactory acoustic field characteristics in reverberation rooms is demonstrated. Such procedures would target the spaces used to measure the acoustic insulation of samples without the need to install any sound diffusing and absorbing elements in their interiors.

2. Subject of study

The research presented in this paper was carried out on two original test benches. The former was an available in the laboratory coupled reverberation rooms made in a small scale (hereinafter named: small reverberation rooms), the latter was a full-size room designed in accordance with the restrictions of the future user (hereinafter named: large reverberation rooms). The first stand, allowed for pilot studies to be carried out on smaller samples. This approach, which is often used in scientific research (Balmori *et al.*, 2024; Djambova *et al.*, 2022) was far more economical and quicker to implement at the initial stage of research. The pilot studies were aimed at verifying the adopted research methodology and determining preliminary conclusions regarding the impact of sound diffusing and sound absorbing elements on the acoustic field in exemplary reverberation rooms. At the second stand, the target case was studied, i.e., the acoustic field inside the individually designed full-size rooms. These results directly reflected reality without the risk of scale influence on the results obtained. A detailed description of these two stands is provided in Subsecs. 2.1 and 2.2, respectively.

2.1. Small reverberation rooms

Tests on small-scale samples were conducted in small, coupled reverberation rooms (see Fig. 1) which replicated the full-size reverberation rooms located at the Department of Mechanics and Vibroacoustics of AGH University of Science and Technology. Quoting Szeląg *et al.* (2021), Fig. 2 shows the detailed dimensions of this measurement stand. Both rooms, source and receiving, had a volume of about 0.35 m^3 (which is almost 180 m^3 at 1:1 scale). As described in the aforementioned article, the rooms were effectively vibration-isolated from each other and from the ground. Moreover, due to the fact that for the purposes of acoustic insulation tests there is no need to scale the parameters of the gas filling the rooms, the interiors could remain filled with atmospheric air. During individual measure-

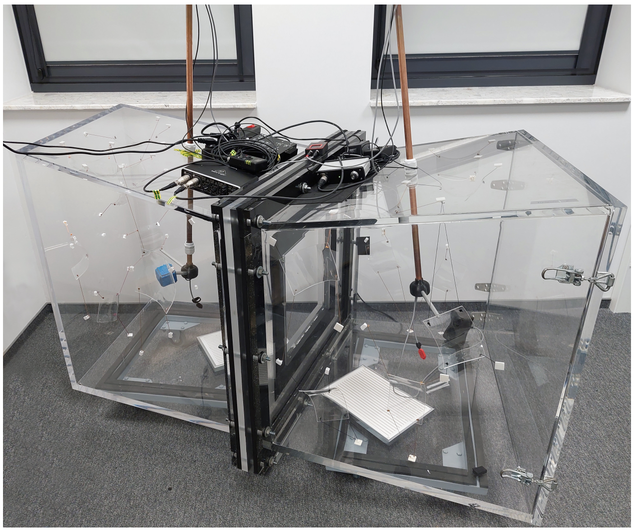


Fig. 1. Small reverberation rooms made of 20 mm-thick plexiglass panels.

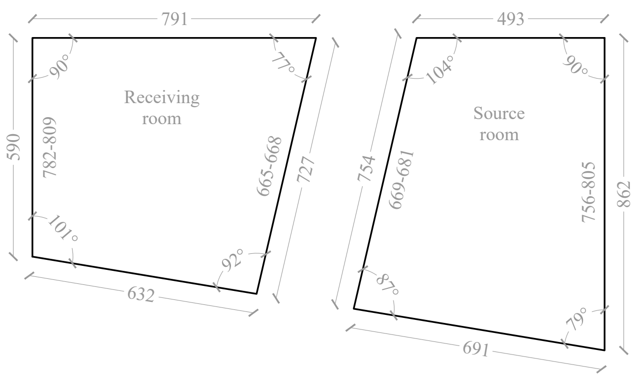


Fig. 2. Dimensions [mm] of the small reverberation rooms; the intervals define the walls heights that vary along the width (Szeląg *et al.*, 2021).

ment sessions, only the consistency of air parameters such as pressure, temperature and air humidity was monitored, and finally, based on the results of reverberation time (RT) measurement in receiving room, the influence of acoustic absorption of the interior on measured sound pressure levels (SPLs) was removed.

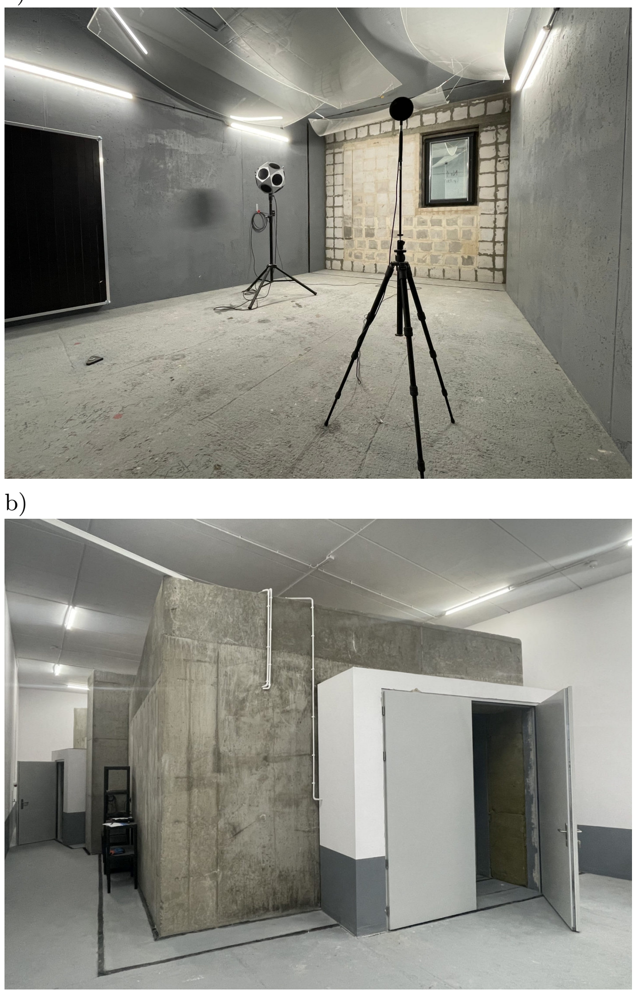
During the subsequent test stages shown in this paper, in the reverberation rooms, diffusors made of sound-reflecting plexiglass panels were installed. In the source room, eight pieces with dimensions of 100 m × 150 m × 2 mm and two with dimensions of 150 m × 150 m × 2 mm were ultimately mounted. In the receiving room, seven pieces with dimensions of 100 m × 150 m × 2 mm and three with dimensions of 150 m × 150 m × 2 mm were ultimately mounted. The plexiglass panels were pre-curved to provide better sound diffusion properties. In addition, on the floor of both reverberation rooms, one slotted sound absorbing structure was placed. This absorber was made of 15 mm-thick foam covered with 3 mm-thick aluminum plate with 1 mm-wide slots incised at 10 mm intervals. The overall dimensions of each absorber were 310 m × 220 mm.

The measurement stand consisted of the following components: two custom made high-frequency sound sources, two 1/4″ 46BE G.R.A.S. microphone sets, two 12AL G.R.A.S. amplifiers, UMC204HD BEHRINGER U-PHORIA measurement card and a dedicated computer script in the MATLAB environment for processing measurement results (for the detail description of the measurement stand see (Szeląg *et al.*, 2021)). This article also proves that both the scaled measurement stand, and the measurement methodology meet the requirements of (ISO, 2021a; 2021b; 2021c) adapted to the scale factor as well as that the uncertainty of measurements on the tested stand meets the requirements of (ISO, 2014) for maximum uncertainty values. Therefore, the reliability and repeatability of measurement results obtained on this stand was confirmed.

2.2. Large reverberation rooms

For the full-size tests, two coupled reverberation rooms (see Fig. 3) located in the laboratory Mobilne Laboratorium Techniki Budowlanej Sp. z o.o. in Wałbrzych were used. These rooms were designed and made in accordance with the standard requirements (ISO, 2021b; 2021c), taking into account certain architectural limitations. The detailed dimensions of the source and receiving rooms are shown in Fig. 4. The volumes of the source and receiving rooms were 77 m^3 and 57 m^3, respectively. The reverberation rooms were constructed of reinforced concrete structure with a wall thickness of 30 cm. The rooms were divided by a reinforced concrete frame with a cross section of 100 cm × 100 cm. The rooms and the frame were decoupled and vibration-isolated from each other and from the surroundings. Each room was accessed via a dedicated acoustic sluice equipped with two doors. The acoustic sluice structure was decoupled and vibration-isolated from the rooms and from the surroundings. A single-wing door was fitted in the receiving room, while a double-wing door was used in the source room for technological reasons, i.e., to allow large measurement samples to be brought in.

a)



b)

Fig. 3. Exterior view of the large reverberation rooms from the side of the source room (a) and interior view of the source room (b).

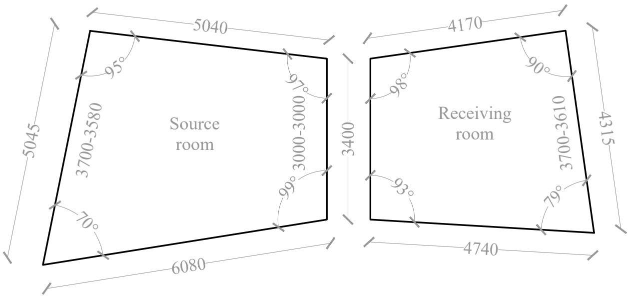


Fig. 4. Dimensions [mm] of the large reverberation rooms; the intervals define the walls heights that vary along the width.

During the subsequent test stages shown in this paper, in both reverberation rooms, diffusers made of sound-reflecting plexiglass panels were installed. Ultimately, three diffusers of dimensions 3000 mm × 1000 mm × 6 mm and three of dimensions 2000 mm × 1000 mm × 6 mm were installed in the source room as well as in the receiving room. The panels suspended from the ceiling and on the walls were bent due to their own weight, resulting in an even better sound diffusion effect. In addition, in both rooms, one slotted sound absorbing structure was mounted on the wall. This absorber was made of 100 mm-thick wool covered with 21 mm-thick board with 4 mm-wide slots incised at 65 mm intervals. The overall dimensions of each absorber were 1850 mm × 1050 mm.

The measurement stand consisted of the following components: an omni-directional sound source B&K 4292-L-001, a power amplifier B&K 2734, two measurement microphones B&K 4189 together with preamplifiers B&K ZC0032, a two-channel sound analyser B&K 2270A and a computer program for building acoustics B&K 7830.

3. Methodology

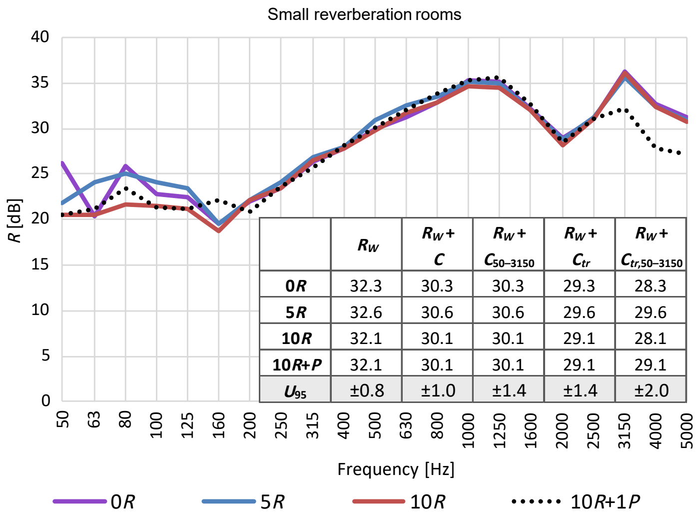
The studies presented in this paper were carried out in three stages at each of the measurement stand. In stage 1, the acoustic airborne sound insulation of selected test samples was measured in reverberation rooms, without using any additional sound diffusing nor sound absorbing elements. In the small reverberation rooms, a plexiglass sample with dimensions of 12.5 mm × 25.0 mm and a thickness of 1 mm was tested, while in the large reverberation rooms, a door with an area of 2.47 m^2 was tested. The following criteria guided the selection of measurement samples. Firstly, the scale and full-size samples were supposed to have similar dimensions after taking into account their scaling, and this was achieved. Secondly, the samples had to have low sound insulation so that the test results were not dependent on the flanking sound transmission. At this point it is worth noting that it is not important whether the scale sample has a full-size equivalent or the samples tested at both measurement stands are the same. The aim of the research was to determine the acoustic field in the rooms and its impact on the measurement results, and not to verify the insulation of the samples themselves or to check the measurement capabilities and validate the test stands.

Measurements were taken in accordance with the guidelines of (ISO, 2021a). In both source and receiving rooms, the SPL was recorded at ten different measurement points, five for each of the two sound source positions. The averaging time for a single measurement was 15 seconds. The RT was measured in both the source and receiving rooms. For the measurement in small reverberation rooms the impulse response integration method based on the swept sine signal was used, while in the large rooms the intermittent noise method was adopted. The tests carried out at the subsequent stages followed the same path as in stage 1, except that in stage 2 in the reverberation rooms additional sound diffusing elements were installed in batches, while in stage 3, a sound absorbing structure was placed in each reverberation room. All measured sound insulation indicators were supplemented with measurement uncertainty values U_{95} determined in accordance with ISO (2020a) assuming the measurement situations C (standard uncertainty of measurement repeatability) – appropriate values read from Tables 2 and 3 in the standard (Wittstock, 2015).

4. Measurement results and discussion

4.1. Measurements in small reverberation rooms

Figure 5 shows the results of the acoustic insulation measurement for a sample tested in the small reverberation rooms in four different variants of interior acoustic adaptation, i.e., for different numbers of sound diffusing elements and with or without the sound absorbing structure. The results, after scaling them to actual measurement frequencies (Sonin, 2001) are presented in the full frequency range typical for such tests, i.e., 50 Hz–5000 Hz. The graph also provides information on the values of the sound insulation single-number quantities of the sample, R_w, $R_w + C$, $R_w + C_{50-3150}$, $R_w + C_{tr}$, and $R_w + C_{tr,50-3150}$ calculated according to (ISO, 2020b), for each of the alternatives tested. All indicators presented in Fig. 5 are supplemented with measurement uncertainty values U_{95} determined in accordance with (ISO, 2020a). The conclusions from the analysis of the data contained in Fig. 5 are as follows. After introducing a large number of sound diffusing elements, that is 10 pieces into each reverberation room, a decrease in R-values in the low-frequency bands (50 Hz–125 Hz) can be observed. In addition, the acoustic insulation characteristics in the 160 Hz band evened out after the installation of sound absorbing structures in the rooms. The observed deviations between test results for individual measurement variants are of statistical significance, as in most bands in the indicated frequency range they are higher than standardised values. In the other frequency bands, i.e., from 200 Hz upwards, the diffusing and sound absorbing elements had no significant impact on the sound insulation characteristics. The noticeable decrease in sound insulation in the 3150 Hz–5000 Hz bands for the variant with sound absorbing elements occurred due to a reduction in the SPL in the source room because of the interior damping, and consequently an insufficient separation between the signal and the background noise in the receiving room. The sound insulation values in these frequency bands are



	R_W	R_W+C	$R_W+C_{50-3150}$	R_W+C_{tr}	$R_W+C_{tr,50-3150}$
0R	32.3	30.3	30.3	29.3	28.3
5R	32.6	30.6	30.6	29.6	29.6
10R	32.1	30.1	30.1	29.1	28.1
10R+P	32.1	30.1	30.1	29.1	29.1
U_{95}	±0.8	±1.0	±1.4	±1.4	±2.0

f [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
U_{95}	3.9	3.5	3.1	2.7	2.4	2.0	1.8	1.6	1.4	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2

Fig. 5. Acoustic insulation of the sample tested in the small reverberation rooms in four different variants of interior acoustic adaptation: $0R$ – no diffusing elements in the reverberation rooms; $5R$ – five diffusing elements in each room; $10R$ – ten diffusing elements in each room; $10R+1P$ – ten diffusing elements and one sound absorbing element in each room. The results from the small rooms are scaled to actual measurement frequencies.

therefore underestimated. It is worth mentioning that the variation in the sound insulation values in the low-frequency bands were not strongly reflected in the values of the single-number quantities. Differences in the values of individual indicators are smaller than their measurement uncertainty.

In order to verify the acoustic field in the source and receiving rooms, the SPL spectra in the rooms were plotted in Fig. 6 for all analysed measurement variants. The graphs also show the scatter of the results as a difference of the maximum and minimum SPL obtained in a given frequency band between in-

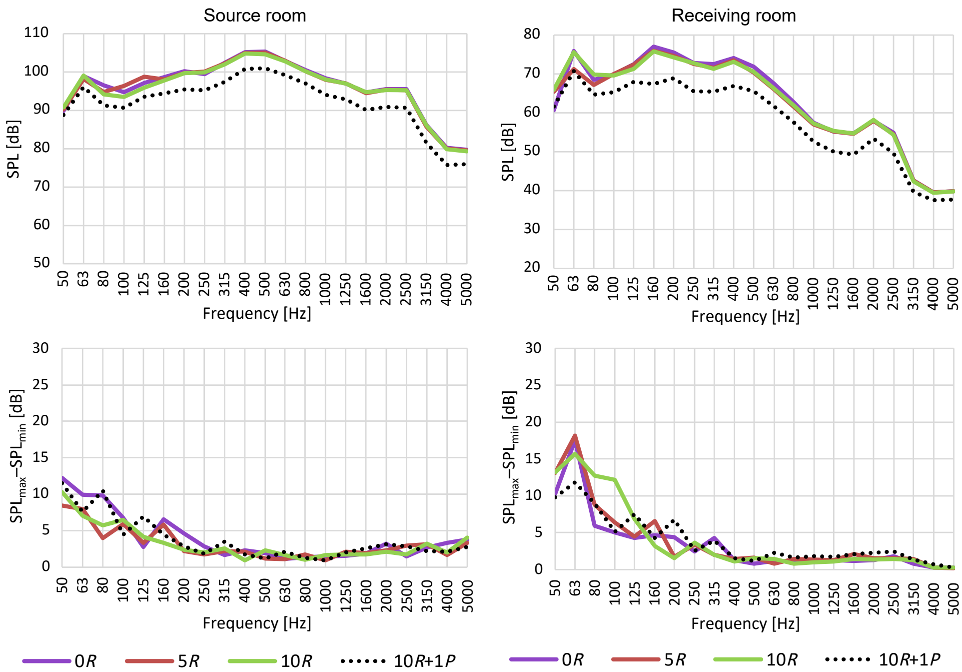


Fig. 6. Equivalent SPL and scatter of the results between individual measurement points in the small source and receiving rooms in four different variants of interior acoustic adaptation: $0R$ – no diffusing elements in the reverberation rooms; $5R$ – five diffusing elements in each room; $10R$ – ten diffusing elements in each room; $10R+1P$ – ten diffusing elements and one sound absorbing element in each room. The results from the small rooms are scaled to actual measurement frequencies.

dividual measurement points. An analogous comparisons are presented in Fig. 7 for the values of RT in the rooms.

Based on Fig. 6, it can be stated that the equivalent SPLs in both the source and receiving rooms do not differ significantly for interiors with different numbers of diffusing elements. Only the addition of sound absorbing structures reduces the SPL in the rooms, which is obviously due to the partial absorption of sound by such elements. Moreover, no significant trend can be observed in the variation of SPLs values for the different measurement points depending on the number of diffusing and absorbing elements in the rooms. At most, an improved homogeneity of the results in the 63 Hz band may be noticed in the receiving room after installing the sound absorber. This band was characterised previously by the greatest inhomogeneity of the sound field. It can also be added that slightly greater scatter of the results in the low-frequency bands is obtained for the receiving room. However, for the highest frequency bands the results scatter in this room decreases due to the overlap between the signal value and the background sound level generated by the measurement path itself.

Figure 7 shows that with the increasing number of sound diffusing elements and adding a sound absorbing structure, the RT in both source and receiving rooms decreases. In the case of the diffusing elements, it should be noted that this is not a result of sound absorption by this type of elements, as they were made of sound-reflecting plexiglass. This occurs due to the improved diffusion of the sound field in the rooms, the shortening of the path between reflections and the increase in the number of reflecting planes. Importantly, the use of sound diffusing elements only is not sufficient to achieve the RT recommended by ISO (2021c). Additional sound absorbing elements are required. Such structures installed in the tested rooms made it possible to meet the standard requirements in the basic frequency range of 100 Hz–3150 Hz, except for 100 Hz in the receiving room. In order to meet the standard requirement in the full frequency range (from 50 Hz), it would be necessary to add a low-frequency sound absorbing structure tuned to frequency 80 Hz, for which the measured values of RT are the highest. Based on the plots showing the scatter of the RT values between the individual measurement points, it can be concluded that the increase of the number of sound diffusing elements and addition of a sound absorbing structure reduces this scatter, however, some deviations from this rule are noticeable in selected frequency bands. Nevertheless, the obtained scatter of the results is not high in all measurement cases, which indicates a quite good diffusion of the sound field inside the small reverberation rooms.

In summary, the following conclusions can be drawn from the tests carried out in the small reverberation rooms. The sound fields in terms of spatial uniformity are similar in both reverberation rooms. Even without diffusing and absorbing elements, a quite good

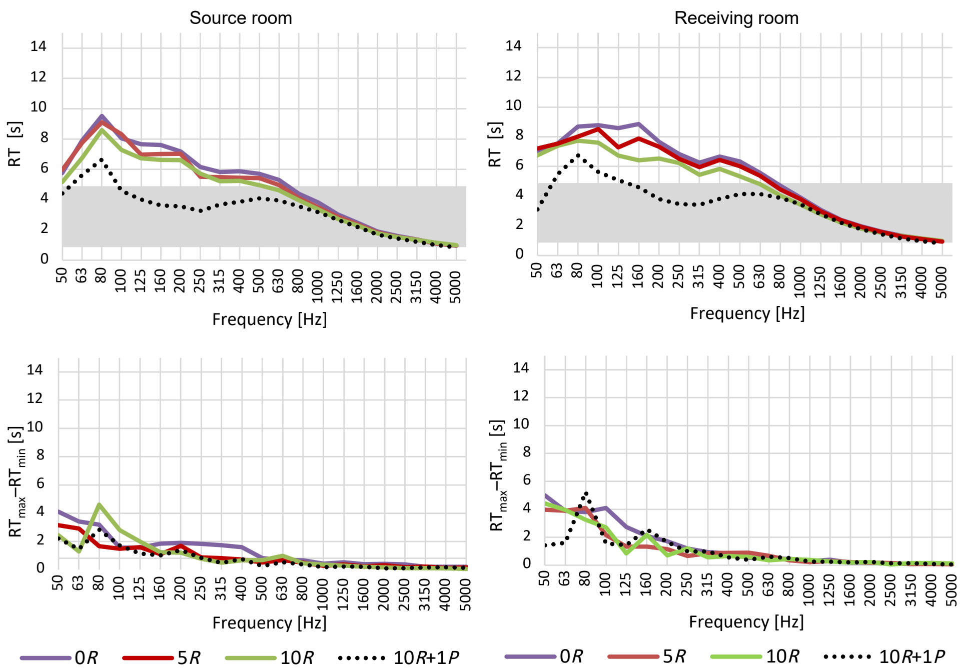


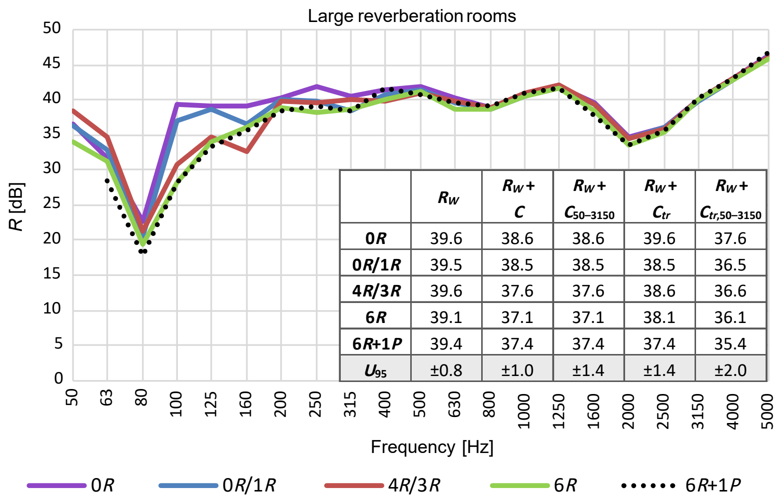
Fig. 7. RT and the scatter of the results between individual measurement points in the small source and receiving rooms in four different variants of interior acoustic adaptation: $0R$ – no diffusing elements in the reverberation rooms; $5R$ – five diffusing elements in each room; $10R$ – ten diffusing elements in each room; $10R{+}1P$ – ten diffusing elements and one sound absorbing element in each room. In the RT diagrams, the grey colour indicates the RT ranges recommended by ISO (2021c) standard for the respective room. The results from the small rooms are scaled to actual measurement frequencies.

homogeneity of the results for both the rooms was obtained, i.e., the scatter in SPLs and values of RT in individual measurement points did not deviate from typical values obtained in other laboratories (compared to (Nutter *et al.*, 2007) and (Vallis *et al.*, 2015)). Nevertheless, in order to achieve the recommended RT in the rooms, it was necessary to add sound diffusing and sound absorbing elements. However, the results presented in Fig. 5 show that the use of sound diffusing elements in the context of the correct value of the sample sound insulation was necessary only in the low-frequency bands. Further reduction of the RT to the recommended values by installing the absorber had no effect on the sound insulation value of the samples. In conclusion, the analysed small reverberation rooms are characterised by a quite good spatial homogeneity of the sound field, nonetheless they require the use of additional diffusers in order to obtain the correct sound insulation values.

4.2. Measurements in large reverberation rooms

Figure 8 shows the results of the acoustic insulation measurement for a sample tested in the large reverberation rooms in five different variants of interior acoustic adaptation, i.e., for different numbers of sound diffusing elements and with or without the sound absorbing structure. The graph also provides information on the values of the sound insulation single-number quantities of the sample, R_w, R_w+C, $R_w+C_{50-3150}$, R_w+C_{tr}, and $R_w+C_{tr,50-3150}$ calculated according to (ISO, 2020b), for each of the alternatives tested. All indicators presented in Fig. 8 are supplemented with measurement uncertainty values U_{95} determined in accordance with ISO (2020a). The conclusions from the analysis of the data contained in Fig. 8 are as follows: a decreasing trend of R-values in the low-frequency bands (50 Hz–315 Hz) can be observed with more sound diffusing elements being introduced into the rooms. The observed deviations between test results for individual measurement variants are of statistical significance, as in all bands in the indicated frequency range they are higher than standardised values. In the other frequency bands, i.e., above 315 Hz, sound diffusing and sound absorbing elements had no significant effect on the sound insulation characteristics of the sample. It is worth mentioning that the variation in the sound insulation values in the low-frequency bands were also reflected in the values of the single-number quantities. Differences in the values of most indicators, only except R_w, are larger than their measurement uncertainty, so they are of statistical significance.

Similarly, as for the case of the small reverberation rooms, in order to verify the acoustic field in the source and receiving rooms, the SPL spectra in the rooms were plotted in Fig. 9 for all analysed measurement variants. The graphs also show the scatter of the results as a difference of the maximum and minimum SPL obtained in a given frequency band between individual measurement points. An analogous comparisons are presented in Fig. 10 for the values of RT in the rooms.



f [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
U_{95}	3.9	3.5	3.1	2.7	2.4	2.0	1.8	1.6	1.4	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2

Fig. 8. Acoustic insulation of the sample tested in the large reverberation rooms in five different variants of interior acoustic adaptation: $0R$ – no diffusing elements in the reverberation rooms; $0R/1R$ – no diffusing elements in the source room and one diffusing element in the receiving room; $4R/3R$ – four diffusing elements in the source room and three diffusing elements in the receiving room; $6R$ – six diffusing elements in each room; $6R+1P$ – six diffusing elements and one sound absorption element in each room.

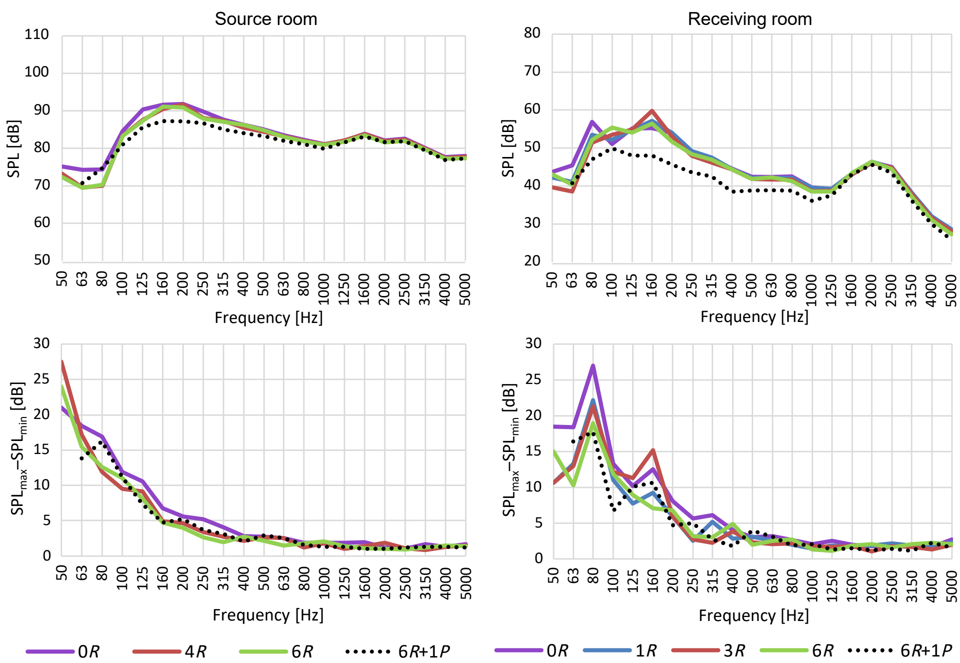


Fig. 9. Equivalent SPL and scatter of the results between individual measurement points in the large reverberation rooms in five different variants of interior acoustic adaptation: $0R$ – no diffusing elements in the rooms; $0R/1R$ – no diffusing elements in the source room and one diffusing element in the receiving room; $4R/3R$ – four diffusing elements in the source room and three diffusing elements in the receiving room; $6R$ – six diffusing elements in each room; $6R$+$1P$ – six diffusing elements and one sound absorbing system in each room.

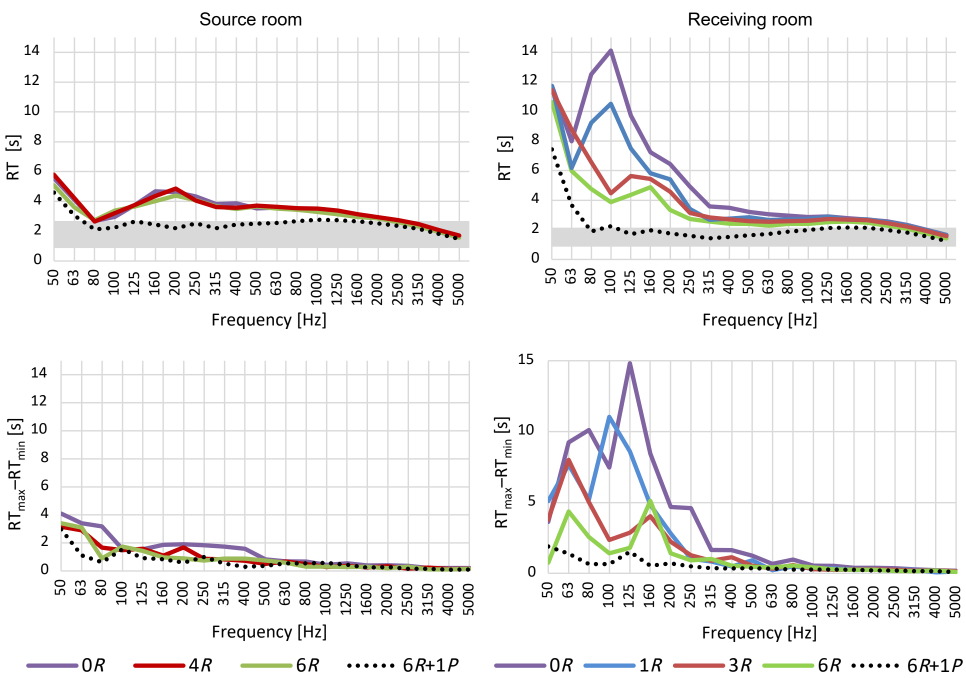


Fig. 10. RT and the scatter of the results between individual measurement points in the large source and receiving rooms in five different variants of interior acoustic adaptation: $0R$ – no diffusing elements in the rooms, $0R/1R$ – no diffusing elements in the source room and one diffusing element in the receiving room, $4R/3R$ – four diffusing elements in the source room and three diffusing elements in the receiving room, $6R$ – six diffusing elements in each room, $6R$+$1P$ – six diffusing elements in each room and additionally one sound absorbing system. In the RT diagrams, the grey colour indicates the RT ranges recommended by ISO (2021c) standard for the respective room.

Based on Fig. 9, it can be stated that the equivalent sound levels in both the source and receiving rooms do not differ significantly for interiors with different numbers of sound diffusing elements, except when there are no such elements in the rooms. In the latter case, the sound level in the low-frequency bands (below 100 Hz) is slightly higher. Through the addition of sound absorbing structures, the sound level is reduced in the rooms. Moreover, a certain dependency can be observed between the number of sound diffusing and absorbing elements and the scatter of measured values in individual points. It is the most evident in the case of receiving room at the frequency 80 Hz, for which the scatter of the values is the highest.

The graphs shown in Fig. 10 illustrate a very interesting phenomenon. On the one hand, in the source room the RT does not depend on the number of diffusing elements used, and the scatter in the results between the individual measurement points only slightly decreases as the number of such elements increases. The installation of the absorbing element in the source room ultimately reduces the RT, allowing the standard requirements to be met in the bands from 80 Hz upwards. In the receiving room, on the other hand, the RT is extremely dependent on the number of sound diffusing elements, especially in the low-frequency bands, where the difference in values reaches up to 10 s in the 100 Hz band. The situation is analogous for the scatter in the results between the individual measurement points. With a larger number of diffusing elements, these values decrease significantly. Of course, even better results are obtained with the introduction of the sound absorbing structure, both in terms of RT values, where the standard requirements are met from as low as 80 Hz, and in terms of scatter, which is rather small for this situation. Interestingly, the initial values of the RT for the situation where there were no diffusing and absorbing elements in the rooms were significantly higher in the receiving room than in the source room, even though the receiving room has a smaller volume than the source room, so theoretically the situation should be the opposite. In the source room, in principle, the use of diffusing elements was unnecessary, as the initial results demonstrate the homogeneity of the sound field. Alternatively, a sound absorbing structure could have been used to reduce the RT to the value recommended by ISO (2021c) standard. However, this was not necessary, as the standard recommends reducing the RT only if it can have a significant effect on the sound insulation results, which is not relevant to the analysed situation. The situation is quite different in the case of the receiving room. Here, the use of diffusing elements was necessary to control the sound field inside the room. These elements significantly reduced the RT in the room, but not because they had sound absorbing properties, but because they scattered the sound waves in the room and ensured that the sound field was uniform. The additional sound absorbing structure further improved the situation, especially in terms of the scatter of measurement results.

In summary, the results of measurements carried out in the receiving room were extremely surprising. In the absence of diffusing elements, the room was virtually unsuitable for testing. The falsely inflated RT values (significantly higher than in the larger source room) significantly affected the final sound insulation of the sample (see Fig. 8). A completely different situation concerns the source room. From the point of view of the accuracy of the results, no additional sound diffusing and absorbing elements could actually be used in the source room. The presented measurement results raise the question as to why there are such unfavorable acoustic conditions in the receiving room and if this could have been avoided at the design stage. As mentioned at the beginning of the article, the ISO (2021b) standard gives quite a lot of freedom in choosing the geometry of reverberation rooms and does not impose the need for any procedure to verify the effect of the geometry design on the acoustic parameters of the interior at the design stage. It is only at the post-construction stage of the reverberation rooms that the acoustic field inside is verified and, if necessary, additional sound diffusing or sound absorbing elements are installed. The authors therefore intend to verify whether it was possible to predict at the design stage that the interior acoustic parameters of the receiving room would not be satisfactory and thus introduced a modification of the room geometry to avoid the need to install sound diffusing or sound absorbing elements undesirable by users.

The basic tools used in modeling of interior acoustics are computer programs based on the image-source method, such as: CATT Acoustic, ODEON, EASE. However, according to (Kuttruff, 2000) such a method is reliable only in the frequency range above the so-called Schroeder frequency. In the case of the analysed receiving room, the Schroeder frequency is 496 Hz, and for the source room it is 430 Hz. It should therefore be concluded that this is not a suitable method for the present design case, as well as for the design of other typical reverberation rooms. The above conclusion is illustrated by the graph presented in Fig. 11 which presents a comparison of the measured and simulated in CATT-Acoustic RT curves for the studied receiving room. As can be seen, the simulated RT values coincide from 500 Hz onwards with the measured values. Below 500 Hz, the curves diverge, and the measured RT takes on significantly higher values than the simulated one.

In the next step, the correctness of the design of the reverberation rooms was verified using the Bonello criteria (Bonello, 1981). These criteria relate to the distribution of the room's intrinsic moduli, and their fulfilment is intended to ensure the uniformity of the

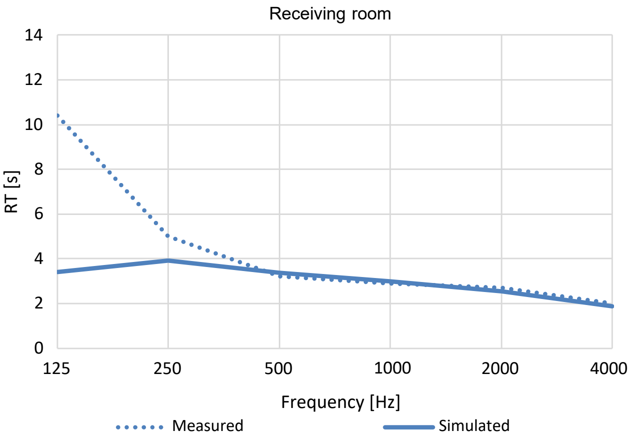


Fig. 11. RT measured and simulated in CATT-Acoustic software in the large receiving reverberation room. The simulation parameters were as follows: 50 000 rays, model 1, consideration of air sound absorption, ray tracing for 4500 ms, three source positions and ten microphone positions.

acoustic field in the interior and the minimisation of wave phenomena. The first criterion requires that the number of modes per 1/3 octave frequency band is to be a non-decreasing function. The second criterion requires that there are no modes of overlapping frequencies. Alternatively, overlapping modes are allowed in these 1/3 octave bands where the number of modes is minimum 5. In the analyses presented in this paper, a distance between modes of less than 1 Hz was adopted as the criterion for overlapping mods. The number of reverberation room eigenmodes were determined in two ways. The first way assumed analytical calculations using the equation proposed by Morse and Bolt (1994):

$$N = \frac{4\pi f^3 V}{3c^3} + \frac{\pi f^2 S}{4c^2} + \frac{fP}{8c}, \tag{1}$$

where N is the number of modes from 0 Hz up to f Hz, f is the frequency [Hz], V is the room volume [m^3], S is the room surface area [m^2], and P is the total room perimeter [m]. In the second method a finite element method (FEM) modal analysis was carried out in the ANSYS environment. In the simulations, a mesh division into 10 cm finite elements was adopted. Figure 12 presents the results of the analyses for the 1st Bonello criterion carried out by both the analytical method and using computer simulations. Firstly, there is a very poor agreement between the results obtained by the analytical method and the FEM simulation results. Nevertheless, all results show that the 1st Bonello criterion is met in both the source and receiving rooms. Next, the overlap of eigenmodes in the different 1/3 bands was compared, as indicated by the 2nd Bonello criterion. Although the overlapping modes were identified, all of them occurred in the 1/3 bands with a minimum number of modes of 5, which

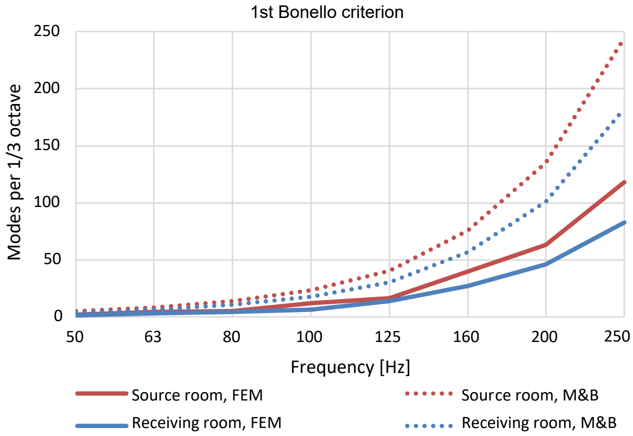


Fig. 12. Results according to the 1st Bonello criterion: eigenmodes of the source and receiving reverberation room determined according to Morse and Bolt equation (M&B) and modal analysis using FEM.

is permissible according to the given criterion. In summary, the Bonello criterion did not identify any irregularities in the receiving room geometry that could cause such a large irregularity in the sound field inside.

Analysing the results of the research presented above, it should be stated that a typical design approach based on theoretical criteria or computer simulations using the image-source method did not allow for the detection of the problem of a very high irregularity of the acoustic field in the receiving room, which became apparent at the stage of experimental research. Therefore, in the next step, the authors decided to take more advanced actions, i.e., they conducted research on a 1:7 scale model of the problematic receiving room (Fig. 13). A 38 mm-thick chipboard was used to build this model. The measurement stand was the same that was used in earlier scale studies (see Subsec. 2.1).

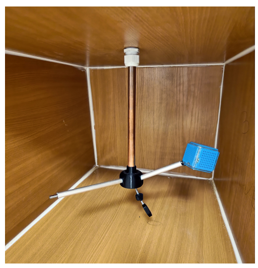
a)  b) 

Fig. 13. 1:7 scale model of the problematic receiving room along with measurement equipment: outside view (a), inside view (b).

Figure 14 shows the comparison of the measured RT values and their scatter between individual measurement points in the full-size receiving room (1:1 scale room) and its 1:7 scale equivalent. Unfortunately, the scale tests do not identify the problem of inhomogeneous sound field in the low-frequency bands (below 250 Hz). The RT at these frequencies does not tend to be as high as it was in the full-sized room.

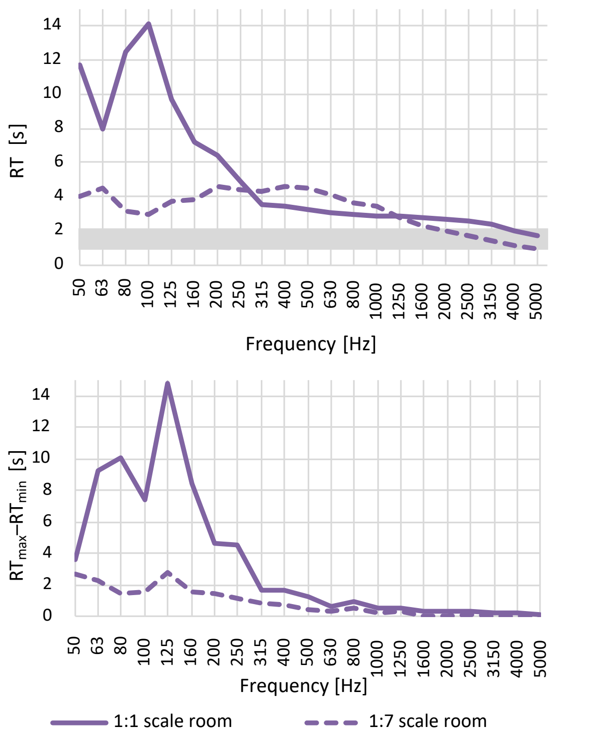


Fig. 14. RT and the scatter of the results between individual measurement points in the full-size receiving room (1:1 scale room) and its 1:7 scale equivalent. In the RT diagram, the grey colour indicates the RT ranges recommended by ISO (2021c) standard.

The scatter of the results is also small in the case of the 1:7 scale room. In the higher frequency bands, the measurement results are much more similar for both rooms. Small differences in the 315 Hz–1000 Hz bands are probably due to the mismatch of the surface sound absorption coefficients between scale and full-size rooms. In the bands above 1600 Hz, the RT in the scaled room is slightly understated because of the significant absorption of sound by the air. It should be remembered that in reality measurements were performed in a frequency range seven times higher.

5. Summary

This paper presents the characteristics of the sound field in the two pairs of coupled reverberation rooms, designed following the guidelines and the requirements of (ISO, 2021c). The results showed that only in one room, i.e., the large source reverberation room, the initial sound field was sufficiently homogeneous such that the room did not require the use of any additional sound diffusing or absorbing elements. These elements, however, were strongly recommended in the other tested rooms. Moreover, in the large receiving reverberation room they were indispensable. The lack of such elements resulted in large discrepancies between measured quantities at individual points, and above all, the recorded RT was significantly overestimated in the low-frequency bands, where unfavourable wave phenomena occurred. This had an impact on the values of sample sound insulation. The obtained values were falsely inflated. As expected, the situation was greatly improved after introducing sound diffusing and absorbing elements in accordance with the ISO (2021b) standard. Nevertheless, diffusing and absorbing elements are not always the preferred option, since they significantly limit the usable space in the rooms and make the installation of samples, sources and measurement points more difficult. Therefore, a situation where the presence of additional diffusing and absorbing elements would not be necessary is desired. Unfortunately, following the design procedures described in the standards or using the typically available design tools, i.e., 1st and 2nd Bonello criterions, numerical simulations with the image-source method and the FEM, it seems impossible to prevent at the design stage the future necessity of using additional diffusing and absorbing elements in the reverberation rooms. Even more advanced research methods, such as measurements using scaled samples, turned out to be unhelpful. Only via verification by measurements performed in the completed rooms provides the assessment if such additional elements are required.

The authors believe that it is necessary to define additional procedures and design guidelines to improve the reverberation rooms design process. Ideally, the resulting acoustic field in the reverberation rooms should be satisfactory without installation of diffusing and absorbing elements. Firstly, the authors intend to carry out more advanced finite element simulations as basic simulations based on modal analysis failed to identify the field problem experienced in a large receiving reverberation room. Secondly, it is planned to expand the scope of research on scaled samples. The lack of convergence of measurement results between a full-size room and its 1:7 scale equivalent is very surprising and requires further verification.

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