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Acoustic analysis of coupled rooms with opposing acoustic properties

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Abstract The article presents the issue of coupled rooms, i.e. a set of interconnected rooms that may interact acoustically. Rooms of this type can be found both in qualified facilities, where their acoustic properties are important and they are appropriately designed, and in ordinary buildings, where their acoustic properties are most often ignored and very random. This study presents a comprehensive acoustic analysis of coupled rooms with opposing acoustic properties – a listening room with a short reverberation time and a reverberant room. Acoustic analyses were carried out experimentally (measurements in a real facility) and numerically (comprehensive computer simulations).

Keywords: coupled rooms, acoustics, reverberation, eigenfrequencies, measurement, numerical simulation, EASE, COMSOL Multiphysics.

1. Introduction

Coupled rooms are a set of at least two interconnected rooms that can interact acoustically. The way they interact with each other is influenced by many factors, including: the volume of individual rooms, the shapes of these rooms, the sizes and locations of coupling apertures, and the acoustic properties of individual rooms. In coupled rooms, the sound decay phenomenon is modified in relation to the sound decay process for analogous rooms but separated from each other. A characteristic feature of many coupled rooms is the occurrence of the double slope decay phenomenon [1,2] in the so-called transmitting room, i.e., an extended sound decay process. This phenomenon is more comprehensible the more reverberant the additional room is.

Coupled rooms can be found both in qualified facilities and in ordinary buildings. In qualified facilities, they usually appear for a reason – their acoustic properties are very important, so they are designed appropriately. Examples include objects of this type found in concert halls, opera houses and theatres, church interiors, and coupled chambers used for acoustic measurements [3,4]. Coupled rooms that appear in ordinary buildings usually have very random acoustic properties, which often negatively affects the comfort of people using these facilities. Examples include open-plan offices, corridor systems or common spaces in individual buildings.

This study presents a comprehensive analysis of coupled rooms with opposing acoustic properties. A pair of rooms was analyzed, one of which was characterized by a reverberant sound field and the other was characterized by a short reverberation time. An example of this type of space is the hall with the exhibition entitled "Krzysztof Penderecki – Heritage of Polish Music of the 20th and 21st Centuries" located in the Krzysztof Penderecki European Centre for Music in Lusławice. Acoustic analyses of the facility were performed both experimentally and numerically. Measurements in the real facility were made based on the relevant standards. Numerical analyses were performed using geometrical methods in the EASE 5 computing environment and using the finite element method in the COMSOL Multiphysics computing environment. The analyses were aimed at assessing the properties of acoustic fields in both rooms and to assess the extent to which the coupling of such opposing rooms would ultimately affect their acoustic properties.

2. Research object

The research object was a complex of coupled rooms constituting a hall with an exhibition entitled "Krzysztof Penderecki – Heritage of Polish Music of the 20th and 21st Centuries" located in the Krzysztof Penderecki European Centre for Music in Lusławice. The analyzed hall has an approximately rectangular shape with dimensions of approx. 30x6x4 m, and its volume is approx. 630 m^3. The hall consists of two oblong rooms connected by two openings located at both ends of the longer side of the rectangle. The first room is characterized by a reverberant acoustic field (reverberation room) and serves as a corridor, while the second room is characterized by a short reverberation time (listening room). The listening room was intended to be a zone where exhibition visitors would be able to listen to music individually. Hence, the acoustics of this room are not accidental. The acoustic design of this facility was prepared by the archAKUSTIK studio. Fig. 1 shows a view of the reverberation room (a) and the listening room (b) of the analyzed hall.

a) b)

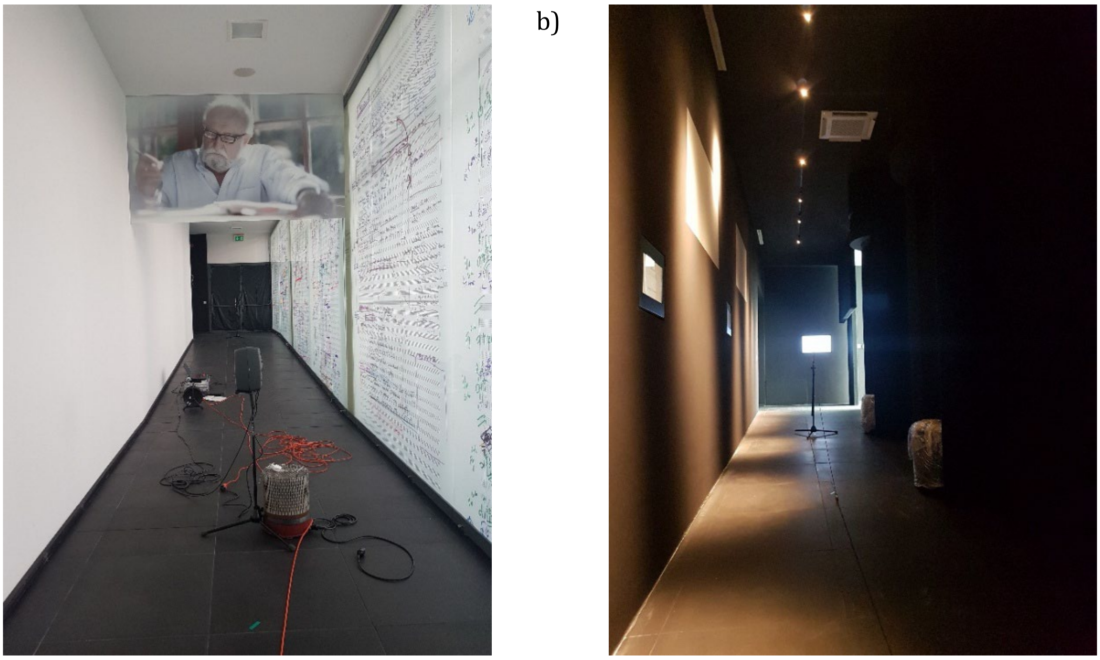

Figure 1. Hall with the exhibition titled "Krzysztof Penderecki – The Heritage of Polish Music of the 20th and 21st Centuries" at the EMC in Lusławice: a) reverberation room, b) listening room.

The listening room is the main exhibition zone. Interesting elements include tubes that create special zones for individual listening. There are 7 such listening tubes located in the facility. The overall décor and acoustic conditions create an atmosphere of intimacy/privacy and promote concentration.

3. Acoustic analyses

In order to assess the acoustic properties of the coupled rooms constituting the hall and the exhibition, a number of analyses were carried out, including: measurements in the actual object, numerical analyses to determine the eigenfrequencies of the object (in the low frequency range) and numerical analyses of the acoustic field in the medium and high sound frequency range.

Fig. 2 shows a diagram of the location of measurement points in the analyzed rooms. This location was used both in measurements in the real object and in numerical simulations. There were 9 measurement points located in the listening room and 3 measurement points located in the reverberation room. Points numbered 2-8 were located at the height of the listening tubes in the listening room. The figure also highlights all the sound source positions used in the analyses. The following numbering was adopted for sound sources: S_1 – sound source located in the center of the listening room, S_2 – sound source located in the center of the reverberation room, S_3 – sound source located in the listening room at the height of measurement point number 1, S_4 – sound source located in the listening room at the height of measuring point number 9.

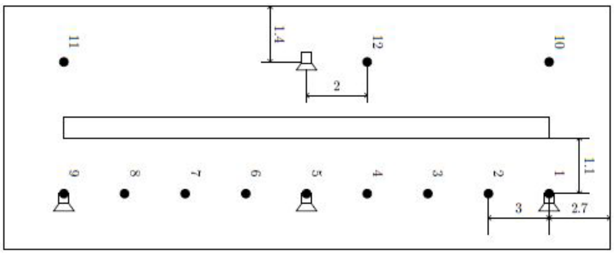

Figure 2. Diagram of the location of sound sources and measurement points.

Fig. 3 shows the room model used in numerical simulations – it is a view from the perspective of the reverberation room.

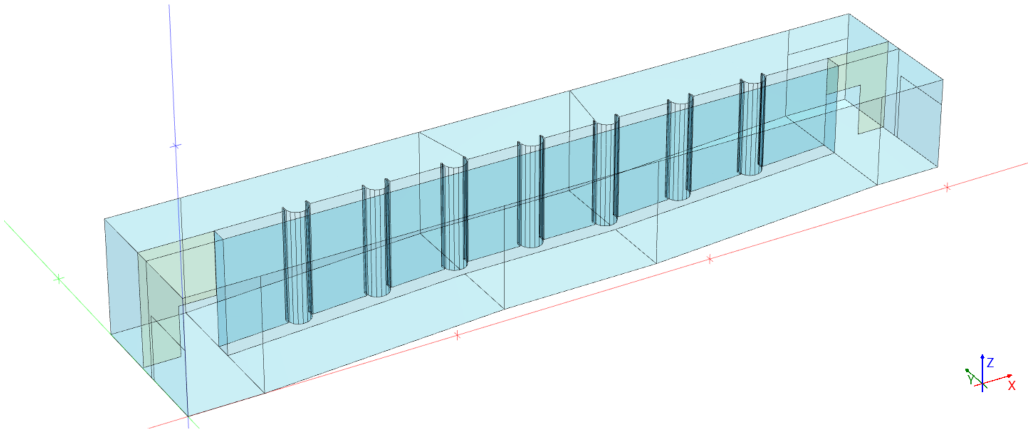

Figure 3. Room model used in numerical simulations.

The numerical model adopted finishing materials analogous to those in the real object. These were: - STO Silent acoustic plaster on the walls in the listening room; Rockfon Mono suspended ceiling – ceiling in the listening room; felt on wool – finishing of tubes in the listening room; marble – on the floors in both rooms; glass, plaster and plasterboard - in the reverberation room.

3.1. Description of the analyzed acoustic parameters

The basic acoustic parameter analyzed was the reverberation time, traditionally defined as the elapsed time for a decay of the sound pressure level by 60 dB after termination of a stationary sound excitation [5]. The reverberation time defined in this way is marked with the symbol T_{60}. However, the study used alternative approaches to determining the reverberation time using a decrease of 20 dB (T_{20}) and 30 dB (T_{30}). In the numerical environment used for calculations, the reverberation time is determined based on the Eyring model [6] as follows:

$$T = k_T \frac{V}{4m \cdot V - S \cdot \ln\left(1 - \alpha_{\text{avg}}\right)}, \tag{1}$$

where $k_T = \frac{24\ln 10}{c} \approx 0.161$ [s·m^{-1}], V is the volume of a room [m^3], S is the total surface area [m^2], α_{avg} is the average absorption coefficient, $m = \frac{1}{10\log(e)}\alpha_{\text{air}}$ is the coefficient for sound attenuation by air [m^{-1}], and α_{air} is the sound attenuation coefficient [dB·m^{-1}].

The second parameter analyzed was the sound pressure level SPL, which is defined as a logarithmic measure of the effective pressure of a sound relative to a reference value and is given in decibels [dB].

The last parameter analyzed was the STI. It was chosen due to the nature of the analyzed object, where the speech signal is the most frequently occurring sound signal. STI is a measure for speech intelligibility. In the software used for calculations, it is determined based on the IEC 60268-16 standard [6, 7].

3.2. Experiment in a real object

Measurements in a real facility were made based on the ISO 3382-1:2009, EN ISO 3382-2:2008/AC:2009 and ISO 16283-1:2014 standards [8-10]. Measurements were made of the background noise level with and without the air conditioning system, reverberation time at various points in the facility and the reduction of sound transmission from the reverberation room to the listening room.

The measured values of the background noise level are summarized in Table 1. The results obtained show that in the listening room, the operation of air conditioning has a very small impact on the listening conditions.

Table 1. Background noise levels [dB] in the listening room and in the reverberation room.

	Without air conditionig	With air conditiong
Listening room	48.0	48.5
Reverberation room	48.0	49.9

In order to determine the reverberation time in the facility, three measurement series were performed at selected points of the analysed facility, and then the obtained values were averaged. The summary of the obtained reverberation time values is presented in Table 2.

Table 2. The values of the reverberation time T_{20} and T_{30} in the hall with exposure obtained by measurement.

Point number	T_{20} [s]	T_{30} [s]
1	0.82	1.04
2	0.73	0.87
3	0.67	0.78
4	0.65	0.76
5	0.72	0.79
6	0.67	0.74
7	0.69	0.81
8	0.76	0.91
9	0.77	0.94
10	2.00	2.05
11	1.90	1.95
12	1.93	1.96

In order to determine the value of sound transmission reduction from the reverberation room to the listening room, three subsequent series of measurements were performed for all previously selected measurement points and using a reference sound source located in the reverberation room (S_2). The reference sound source generated an acoustic signal with a sound pressure level of 88 dB at a distance of 1 m from the sound source. The obtained SPL values are summarized in Table 3.

Table 3. SPL [dB] values in the listening room (1-9) and in the reverberant room (10-12) with the reference sound source located in the reverberant room.

Point number	1	2	3	4	5	6	7	8	9	10	11	12
SPL	74.5	70.2	66.6	64.2	63.3	64.8	67.4	71.7	74.9	84.8	83.8	87.3

3.3. Determining eigenfrequencies numerically

Room modes (eigenmodes) are the natural frequencies at which a room will resonate. These resonances occur because sound waves propagate in the room could create areas of higher and lower acoustic pressure and also standing waves. Eigenmodes are these standing waves which are formed by the interaction of reflected sound waves within the room's boundaries. Eigenmodes depend on the dimensions and the ratio between them for a given room. The occurrence of clear resonances in a room may negatively affect the final quality of the sound field. It can also cause vibrations in elements in the room, such as window panes. On the other hand, when using sound systems, knowing the mode distribution in the room, one can arrange the speakers in such a way that the acoustic effects will be amplified [11].

In the analyzed model it was assumed that all boundaries are perfectly rigid (sound hard boundaries). This means that it returns no information of the damping properties of the room, but the distribution of the pressure should still be reasonably correct [11]. The analyses were performed for frequencies in the range of 0-125 Hz. As a result of the calculations, 210 eigenfrequencies of the object were determined. Table 4 lists the 12 eigenfrequencies with the highest Q-factor values. Fig. 4-5 shows the mode shape in the analyzed object for the two most dominant eigenfrequencies of 65.06 Hz and 118.75 Hz, respectively.

Table 4. List of resonance frequencies [Hz] with the highest Q-factor values.

No.	1	2	3	4	5	6	7	8	9	10	11	12
f	59.43	65.06	72.72	81.93	89.56	93.25	101.24	102.83	107.70	110.59	118.75	121.36

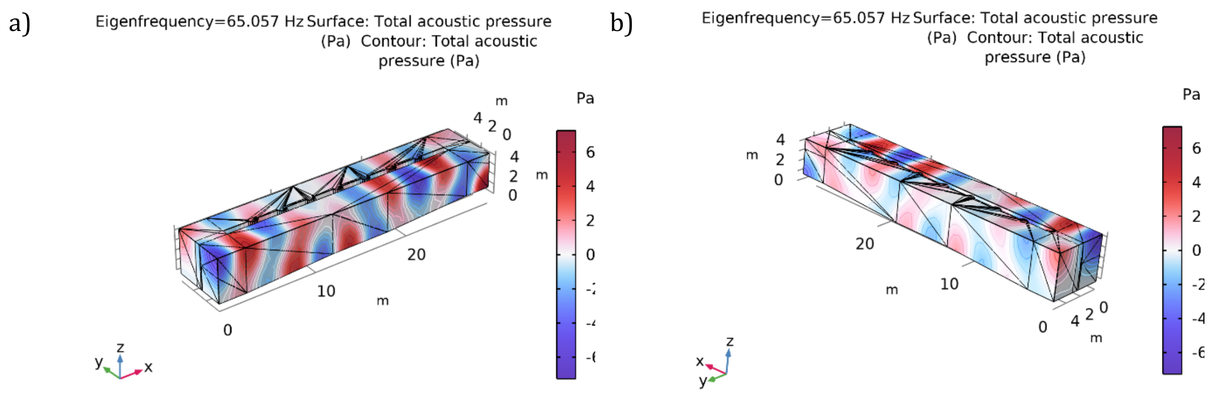

Figure 4. Mode shape for frequency 65.06 Hz: a) reverberation room, b) listening room.

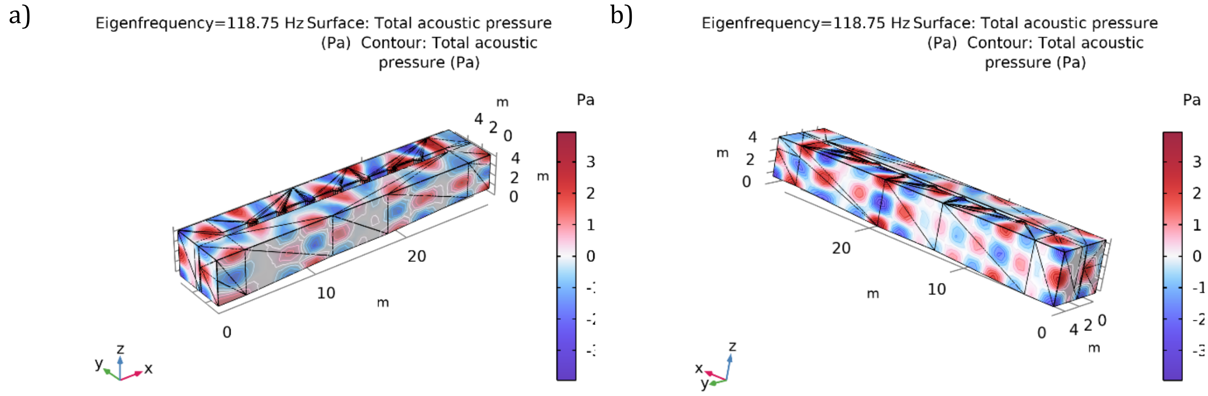

Figure 5. Mode shape for frequency 118.75 Hz: a) reverberation room, b) listening room.

3.4. Numerical calculations in the mid- and high-frequency sound range

The numerical calculation in the audible band was performed using geometrical methods in the EASE 5 SE program in the AURA module. The location of sound sources and measurement points was as shown in Fig. 2 and analogous to the measurements. Numerical simulations were performed both for the measurement points and for the entire internal area. The following parameters were assumed for all simulations performed: resolution: 0.50 m; number of particles: 722000; time length: 1470 ms; absorption model: standard; scattering method: diffuse rain (S-curve, 10%-40%).

The room reverberation time (Table 5) and the values of the SPL and STI parameters were determined numerically.

Table 5. The values of the T_{20} and T_{30} reverberation time and the speech intelligibility index STI in the hall with exposure obtained numerically.

Point number	T_{20} [s]	T_{30} [s]	STI
1	0.92	1.12	0.823
2	0.86	1.18	0.883
3	0.60	0.98	0.916
4	0.47	0.79	0.937
5	0.55	0.62	0.942
6	0.51	0.81	0.931
7	0.74	1.02	0.909
8	0.90	1.16	0.868
9	0.91	1.06	0.816
10	2.14	2.19	0.437
11	2.13	2.19	0.444
12	2.09	2.16	0.494

Analysing the obtained results, it can be concluded that a uniform reverberation field is observed in the reverberant room – this is evidenced by the obtained values of reverberation time and speech intelligibility, which are practically identical in all analysed measurement points. The reverberation time in this room is long, over 2 seconds, which also affects speech intelligibility, which is poor here.

The listening room, on the other hand, is characterized by a much shorter reverberation time and very good speech intelligibility. However, the sound field in this room is not as homogeneous as in the listening room. As might be expected, the closer the coupling apertures are, the lower the quality of the sound field. It should be emphasized, however, that these changes are not large and do not significantly affect listening in this area.

Since the obtained values of the SPL parameter depend on the acoustic power of the sound source used, it was decided to evaluate not the absolute values of this parameter, but the values of its changes (ΔSPL). For this purpose, the acoustic field in the facility was analysed using two identical sound sources located at points S_1 and S_2, approximately in the centres of both areas. Three simulations were performed: 1) only one sound source located at point S_1, 2) only one sound source located at point S_2, 3) two identical sound sources located at points S_1 and S_2. The purpose of this was to determine whether and to what extent a sound source from one room influences the acoustic field in another room, when a sound source generating an acoustic signal is also located in that room. These analyses were also carried out both for individual measurement points and for the entire area. The obtained results are shown in Fig. 6-7.

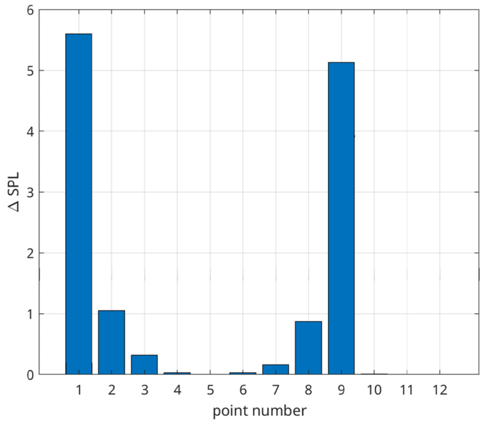

Figure 6. Changes in the SPL parameter value at individual measurement points.

a) b)

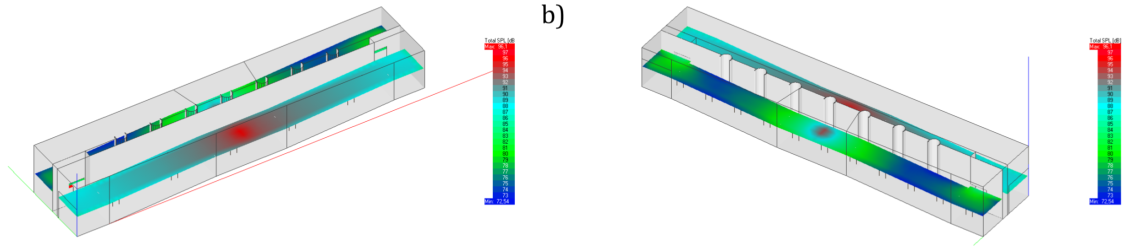

Figure 7. SPL parameter distribution for identical sound sources located in both areas: a) reverberation room, b) listening room.

The SPL parameter analyses were performed in two stages for each room – first, the values were determined for a room with only one sound source located in that room, and then the analysis was performed for two sound sources located in both rooms. On this basis, it was possible to determine the values of changes in the SPL parameter. By analyzing the results for individual measurement points, it can be concluded that the sound source from the reverberation room influences the acoustic field in the listening room only for the points located closest to the coupling apertures. At other points there is practically no influence on the sound field. In turn, when considering the sound field in a reverberation room, it can be stated that with a sound source located in this room and emitting an acoustic signal, the sound source from the listening room has no influence on the sound field.

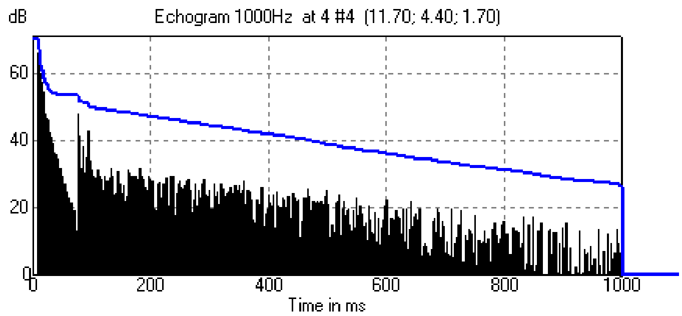

Figure 8. Echogram obtained numerically for point P_4 (short version).

Echograms for the selected measurement points were also determined through numerical analyses. An example echogram for point P_4 is shown in Fig. 8.

Two slope ranges can be distinguished in the presented echogram. The first in the range up to approximately 90 ms and the second – from approximately 90 ms to the end of the analyzed time interval. The echograms for points 2, 3, 6, 7, and 8 behave similarly.

3.5. Summary of experimental and numerical results

In order to assess the accuracy of the numerical analyses performed, the results obtained from measurements and numerical methods were compared. The results of these analyses are presented in Figs. 9-10. Figure 9 shows the absolute values of the T_{20} and T_{30} reverberation time obtained by measurement and numerical methods. Fig. 10 shows the absolute errors for the obtained numerical values.

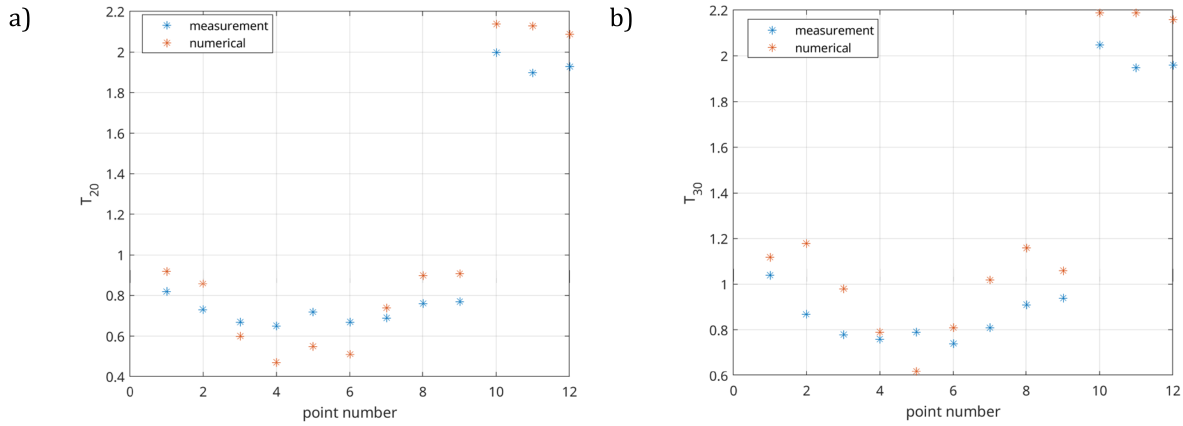

Figure 9. Reverberation time values obtained by measurement and numerical methods: a) T_{20}, b) T_{30}.

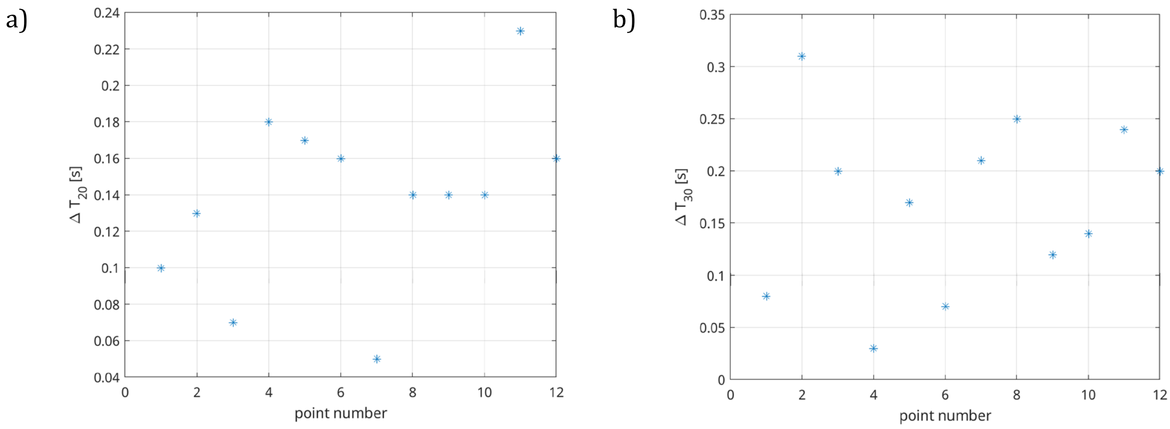

Figure 10. Absolute errors between reverberation time values obtained by measurement and numerical methods: a) T_{20}, b) T_{30}.

Based on the analyses performed, it can be concluded that the obtained results show good agreement. The differences in the obtained values of the reverberation time T_{20} do not exceed 0.2 s, for the reverberation time T_{30} they are slightly worse, but not significantly.

4. Summary and conclusions

The article presents the results of acoustic analysis of coupled rooms with opposing acoustic properties. A series of numerical analyses and measurements performed in the actual facility were made, which allowed for the assessment of both the acoustic properties of individual rooms and their mutual interactions. The results obtained by different methods showed good agreement.

The sound field in a reverberation room is very uniform, characterized by a reverberation time of approximately 2 seconds, which results in poor speech intelligibility. The listening room is much more damped, but the sound field is not as homogeneous. The reverberation time, depending on the location of the measurement point, ranges from approximately 0.5 s for points located closer to the center of the room, to approximately 1 s for points located closer to the coupling apertures. However, despite this, the acoustic properties of the room still ensure very good speech intelligibility throughout its entire area.

By analyzing the mutual influences between the coupled rooms, it can be concluded that the high sound absorption in the listening room results in the sound sources located in this room not affecting the acoustic impressions in the reverberation room. However, sound sources located in the reverberation room may change the sound impression obtained in the listening room in the areas of measurement points 1, 2 and 8, 9. They have no influence on the sound impressions at the other measurement points. Close to the coupling apertures, significantly more reflections appear, the reverberant sound increases in relation to the direct sound, which could be observed in the obtained echograms and which was also observed in other types of coupled rooms [12].

Minor asymmetries can be noticed in the obtained results. They are not the result of errors, but of the fact that the analyzed object is not perfectly symmetrical, because in the area of points 1 and 2 it is higher than in the area of points 8 and 9.

Additional information

The author declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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