PAN
ARCHIVES OF ACOUSTICS
Vol. **44**, No. 4, pp. 739–746 (2019)
DOI: 10.24425/aoa.2019.129729

Effect of Diffusing Elements in a Reverberation Room on the Results of Airborne Sound Insulation Laboratory Measurements

Dominik MLECZKO*, Tadeusz WSZOŁEK

AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
Department of Mechanics and Vibroacoustics
Al. Mickiewicza 30, 30-059 Kraków, Poland
*Corresponding Author e-mail: dmleczko@agh.edu.pl

(*received March 31, 2019; accepted June 18, 2019*)

The main problem in the measurement of airborne sound insulation is the measurement of the sound power radiated by the barrier, in practice performed by measuring the sound pressure level and the acoustic absorption in the receiving room. Large variations of the sound pressure level in a reverberation room indicate the presence of dominating strong standing waves, so that it becomes necessary to install diffusing elements. In ISO 10140, the limits have been defined in which the reverberation time at frequencies at and above 100 Hz should be included. Sometimes, however, in the case of rooms with a large volume, obtaining the required parameters is difficult and sometimes even impossible. It should then be checked whether the measured sound insulation depends on the reverberation time.

The paper presents the results of sound insulation measurements at various reverberation time lengths in subsequent stages of diffusing elements installation in the receiving room. An analysis of diffusing materials amount and arrangement influence on the uniformity of the sound pressure level distribution and reverberation time in the room as well as the value of the measured sound insulation was carried out. Uncertainty of sound insulation measurement with partial uncertainties was adopted as a criterion supporting the assessment of the obtained results.

Keywords: reverberation room; airborne sound insulation; diffuseness.

1. Introduction

Reverberation rooms have been used for a long time for various standardised acoustic measurements, including reverberation sound absorption coefficients, sound insulation of baffles, or acoustic power of sound sources. There is a number of standards defining and specifying the measurement procedures and calculation algorithms for determining the above values. For example, the method of determining airborne sound insulation using reverberation method is given in (ISO 10140-2, 2011; ISO 10140-5, 2010; ASTM E90, 2016), while (ISO 354, 2005) and (ASTM C423, 2017) explain the procedure for measuring the sound absorption coefficient using the same method. These standards also include requirements for reverberation rooms. The main requirement which is the assumption of the method is the existence of diffuse sound field in the room, and the accuracy of the results is strictly dependent on the degree of dispersion (Batko, Pawlik, 2013). It is assumed that in the reverberation room there is a diffusion field which is characterised by spatial homogeneity of acoustic energy density and reverberation time in the entire acoustic field. However, large changes in the sound pressure level in the reverberation room indicate a significant presence of standing waves. In (ISO 10140-5, 2010) the length of reverberation time which should be in the reverberation room under normal test conditions (when the absorption of the tested sample is negligibly small) is determined. If, for low frequencies (from 100 Hz upwards), reverberation time exceeds 2 s or is less than 1 s, it has to be verified whether the sound insulation is not dependent on it.

When such a dependence is stated, appropriate modifications of the reverberation room should be made in order to fulfil the dependence (1):

$$1\ \mathrm{s} \le T \le 2\left(\frac{V}{50}\right)^{2/3} \quad [\mathrm{s}], \tag{1}$$

where V is the room volume [m^3], T is the reverberation time [s].

On the other hand, in (ISO 354, 2005) one can find information that the acoustic field in the reverberation room used for sound absorption measurements should be sufficiently dispersed. Satisfactory dispersal can be obtained by using fixed, hanging diffusing elements or rotating blades.

In (Bradley *et al.*, 2014) the authors used a 1:5 scale model of reverberation room to systematically analyse the relative effectiveness of hanging diffusers versus an alternative diffuser type reffered to as a boundary diffuser. Maximum absorption coefficient, standard deviation of decay rate, and total confidence interval were used to characterise the sound field diffusivity. Analysis reveals that boundary and hanging diffusers produce roughly equivalent diffusion in the sound field. Measurements of sound absorption coefficient of acoustical materials in a reverberation room was investigated in (Toyoda *et al.*, 2004) by numerical analysis based on the ray-tracing method. It was finally confirmed that the sound absorption coefficient of the same specimen can differ much by the effect of the sound diffusers.

In this work, it was verified how the sound diffusers (their number and manner of distribution in the reverberation room) affect the results of sound insulation measurements in laboratory conditions.

2. Test results

2.1. Description of the research object

Laboratory measurements of the sound insulation was carried out in the laboratory equipped with coupled reverberation rooms where the tested material is placed between the rooms. The laboratory is located in the Department of Mechanics and Vibroacoustics of the AGH University of Science and Technology in Kraków. The laboratory consists of two rooms: source room with the volume of 178.77 m^3 and the receiver room with the volume of 176.9 m^3. The rooms are coupled by a measuring window with dimensions 1×2 m. The laboratory meets most of the guidelines contained in the standard (ISO 10140-2, 2011), except for the reduced dimensions of the measuring window (the required area is 10 m^2) (Wszołek, 2007). The cut-off frequency of the receiving room is f_c = 98 Hz.

The measuring path consists of two Norsonic 1/2″ type 1220 pressure microphones, a JBL 2×150 VA loudspeaker, the Sound KRAK 200 VA power amplifier, and two channel Norsonic RTA 840 analyser, at the same time serving as a pink noise generator, which was an acoustic signal used during the measurements. The meteorological conditions, unchanged during the whole measurements, were as follows: temperature – 21°C, relative humidity – 45%, atmospheric pressure – 1010 hPa.

Fig. 1. View of the receiving room along with the measuring hole in the laboratory at AGH University of Science and Technology in Kraków.

The first variant (I) of the tests consisted of performing measurements in an empty room. It turned out that the reverberation time exceeds the value of 2 s (the results of the measurements are presented in Table 2) which was specified in (ISO 10140-5, 2010), and neither it meets the dependence (1) according to which in this room the reverberation time should be in the range from 1 s to 4.6 s. Therefore, it was necessary to verify whether the change in sound field diffusion in the receiving room influences the results of the sound insulation measurement. To improve the diffusion, it was decided to use hanging diffuser elements made of PMMA boards with the thickness of 5 mm. The plate weight is 5.95 kg/m^2. Three versions were used, differing in the number and manner of arrangement of panels in the room:

- Variant II – vertical hanging panels, 2 pcs, with the total area of 6.04 m^2 and dimensions, height × width, respectively: 1×1 m; 0.7×1.2 m; 1.2×1 m; 2×1 m;
- Variant III – vertical hanging panels, 5 pcs, with the total area of 10.18 m^2 and dimensions, height × width, respectively: 1×1 m; 0.7×1.2 m; 1.2×1 m; 2×1 m; 1.2×0.7 m; 1×0.3 m;
- Variant IV – random hanging plates, 3 pcs with the total area 10.18 m^2 and dimensions, height × width, respectively: 1×1 m; 0.7×1.2 m; 1.2×1 m; 1.2×0.7 m; 1×0.3 m – hanging vertically; 2×1 m – bent in the shape of the letter U; 1×1 m hanging horizontally, 1×1 m – hanging at the angle of 45°.

The detailed arrangement of the diffuser plates in the test room is shown in Fig. 2.

2.2. Measuring methodology

The sound isolation from the air sounds is expressed by the formula (2)

$$R_w = 10 \log \frac{P_1}{P_2}, \tag{2}$$

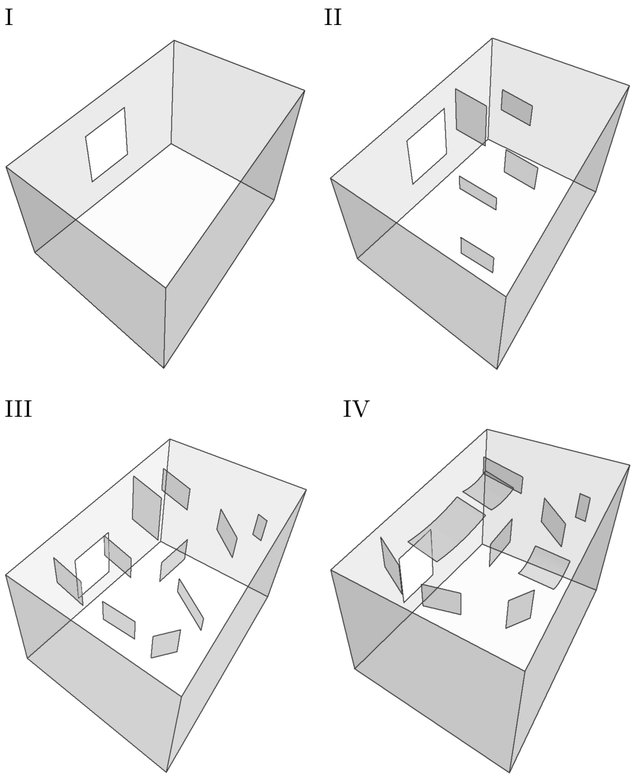

Fig. 2. Arrangement of diffusers in a reverberation room in subsequent variants (fig. Klaudia Staszkiewicz).

where P_1 is the sound power incident on the baffle (proportional to the sound pressure level in the source room, L_1), P_2 is the acoustic power radiated by the baffle (proportional to the sound pressure level in the receiving room, taking into account its acoustic absorption, with the surface of the sample related to 1 m^2).

As a result, formula (2) takes a useful form expressed in formula (3), using the difference in acoustic pressure levels between the source and receiving rooms assuming that the sound fields in both rooms are perfectly diffused and the sound energy is transferred only by the tested material.

$$R = L_1 - L_2 + 10\log\left(\frac{S}{A}\right) \text{ [dB]}, \tag{3}$$

where L_1 is the energy average sound pressure level in the source room [dB], L_2 is the energy average sound pressure level in the receiving room [dB], S is the area of the free test opening in which the tested element is installed [m^2], A is the equivalent sound absorption area in the receiving room [m^2].

It is also necessary to measure sound absorption in the receiving room which is determined from the Sabine formula (4):

$$A = \frac{0.161V}{T}, \tag{4}$$

where V is the volume of the receiving room, [m^3], T is the reverberation time in the receiving room [s].

For each array of diffusing elements, there were 40 measurements (20 positions of microphones at two positions of the sound source) of the sound pressure levels in 1/3 octave bands over an extended frequency range from 50 Hz to 5000 Hz. They were used to determine the spectrum of sound insulation of the tested material and weighted apparent sound reduction index R_w as well as adaptation terms C and C_{tr}. In addition, according to the guidelines contained in (ISO 354, 2005), 20 measurements of the reverberation time T_{30} in the receiving room were made to determine the absorption.

2.3. Measurement uncertainty

If the measurement or prediction result depends on many input parameters, then the uncertainty of this result is the uncertainty function of the partial input parameters (Mleczko, Wszołek, 2010). If they are not correlated, the uncertainty of the final result can be calculated using the law of uncertainty propagation (ISO/IEC Guide 98-3, 2008) (5):

$$u = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial f}{\partial X_{in(i)}}\right)^2 u_i^2}, \tag{5}$$

where u_i is the partial uncertainty of the i-th parameter of the input function f, in the case of acoustic insulation tests defined by the general dependence (3), $X_{in(i)}$ is the i-th input parameter of the function f defining the acoustic insulation according to the formula (3).

In general, the uncertainty of laboratory measurement of sound insulation will be a function of partial uncertainties specified in Eq. (6)

$$u = f\left(u_{L_1}, u_{L_2}, u_{T_2}, u_i, u_a, u_f, u_m\right), \tag{6}$$

where u_{L_1} is the partial uncertainty of the sound pressure level measurement in the source room [dB], u_{L_2} is the partial uncertainty of the sound pressure level measurement in the receiving room [dB], u_{T_2} is the partial uncertainty of the reverberation time measurement in the receiving room, s, u_i is the uncertainty of the measurement (instrumentation) system along with calibration [dB], u_a is the measurement uncertainty (repeatability) of fixing the sample in the test opening [dB], u_f is the measurement uncertainty of the lateral transmission [dB], u_m is the measurement uncertainty caused by the variability of meteorological conditions [dB].

Uncertainties associated with measuring the area of the sample and geometrical parameters of the receiving room were omitted as much smaller than the remaining partial uncertainties. In further calculations, the uncertainty brought by the variability of meteo conditions was not taken into account, as the measurements were made under almost identical conditions (humidity, temperature, and pressure) and the sensitivity of the result to the variability of these parameters is small (Wszołek, 2007). The uncertainty introduced by fixing the test sample (u_a) and the lateral transfer uncertainty were not taken into account, as the tests were performed for one sample, fixed permanently for all variants of tuning the receiving room. The uncertainty brought by the measuring system along with the calibration was adopted equal to 0.5 dB in all frequency bands.

u_{L_1}, u_{L_2} and u_{T_2} uncertainties were determined as standard deviations in 1/3 octave bands for a given measurement session, while propagation coefficients for u_{L_1} and u_{L_2} were assumed to be equal to one, whereas for u_{T_2} as the T_2 function is expressed in the formula (7)

$$\frac{\partial R}{\partial T_2} = \frac{10}{\ln(10 \cdot T_2)}. \tag{7}$$

u_c uncertainty has been calculated assuming that the values of L_1, L_2, and T_2 variables have normal distributions, therefore, according to the central limit theorem, the distribution of the R index also has a normal distribution, therefore, the coefficient of extension k, with the confidence level of 95%, will be 2, $k = 2$

$$u_c = ku = 2u. \tag{8}$$

The measurement uncertainty determined in dependence (8) in the 1/3 octave bands and the R_w indicator is illustrated in the graph in Fig. 5. As it can be seen in this graph, and in particular the tabular values (Tables 1 and 2), both the spread of results and the standard uncertainties of the average reverberation time (in the band from 100 Hz to 3150 Hz) and sound insulation expressed as R_w, slightly decrease with the progressive degree of acoustic adaptation of the receiving room. However, there is no such trend in the individual bands, especially in the low frequency range. The above features indicate the lack of a clear relationship between the degree of acoustic adaptation of the receiving room and the uncertainty achieved, especially in the low frequency range.

Table 1. Results of acoustic insulation measurements in 1/3 octave band, weighted sound reduction index R_w and adaptation terms C and C_{tr} together with the expanded uncertainty $u_{c(95)}$ for the studied distribution variants of diffusers.

f [Hz]	Variant I		Variant II		Variant III		Variant IV	
	R [dB]	u_c [dB]	R [dB]	u_c [dB]	R [dB]	u_c [dB]	R [dB]	u_c [dB]
50	28.4	8.5	29.2	9.4	29.1	8.6	28.2	7.8
63	23.5	7.7	22.2	6.7	23.9	8.1	24.3	8.2
80	18.9	9.6	19.2	10.2	20.9	7.6	19.9	8.3
100	21.4	6.9	23.9	5.9	23.1	6.3	23.6	6.0
125	22.2	4.2	22.9	3.6	21.3	4.7	21.3	4.1
160	21.4	6.4	21.5	5.2	22.8	3.9	23.4	3.6
200	22.6	2.8	22.9	3.0	22.6	3.3	22.5	2.6
250	26.9	2.5	27.0	2.4	26.3	2.3	26.6	2.5
315	27.7	2.5	28.4	2.2	27.9	2.7	28.1	2.3
400	29.7	2.0	29.3	2.0	29.7	1.8	29.7	1.8
500	31.4	2.0	31.1	1.7	31.2	1.8	31.4	1.5
630	32.8	1.7	32.6	1.7	32.7	1.5	32.5	1.5
800	33.8	1.7	34.1	1.7	34.1	1.6	33.7	1.5
1k	35.7	1.6	35.7	1.5	35.6	1.6	35.6	1.4
1.25k	36.7	1.4	36.9	1.4	36.8	1.4	36.8	1.3
1.6k	37.5	1.5	37.7	1.5	37.5	1.6	37.4	1.3
2k	36.8	1.6	37.0	1.4	36.8	1.6	36.7	1.5
2.5k	31.3	1.6	31.7	1.4	31.6	1.6	31.4	1.6
3.15k	30.6	1.6	31.2	1.6	30.9	1.5	30.5	1.5
4k	36.2	1.6	36.7	1.7	36.5	1.7	36.0	1.5
5k	40.1	2.5	40.3	2.5	40.0	2.3	39.5	1.7
R_w	33.0	2.3	33.0	2.0	33.0	2.1	33.0	1.8
C	−1	2.6	−1	2.4	−1	2.4	−1	2.2
C_{tr}	−2	2.5	−2	2.2	−2	2.3	−2	2.0

Table 2. Results of reverberation time T_{30} measurements in 1/3 octave bands in the receiving room for tested distribution variants of the diffusers along with expanded uncertainty $u_{c(95)}$.

f [Hz]	Variant I		Variant II		Variant III		Variant IV	
	T_{30} [s]	u_c [s]	T_{30} [s]	u_c [s]	T_{30} [s]	u_c [s]	T_{30} [s]	u_c [s]
50	10.36	4.81	10.67	4.48	10.72	4.67	10.82	4.56
63	6.63	2.64	6.31	2.90	7.09	2.92	6.39	2.17
80	10.51	4.77	8.95	1.77	8.95	1.17	8.76	1.31
100	10.29	1.73	10.23	1.34	10.03	1.21	9.75	1.29
125	9.98	1.35	10.00	1.73	9.04	1.03	9.06	1.16
160	9.11	1.19	8.78	0.98	9.16	1.27	9.45	1.05
200	8.97	0.67	9.14	1.21	9.06	0.85	8.44	0.67
250	8.83	0.58	8.90	0.86	8.81	0.71	8.21	0.61
315	8.75	0.88	8.68	0.70	8.34	0.59	8.21	0.59
400	7.16	0.53	6.95	0.48	6.97	0.48	6.77	0.52
500	5.72	0.56	5.63	0.37	5.55	0.47	5.52	0.49
630	5.01	0.32	5.01	0.37	4.96	0.34	4.93	0.28
800	5.32	0.29	5.31	0.35	5.29	0.34	5.29	0.28
1k	5.90	0.27	5.85	0.32	5.82	0.27	5.79	0.33
1.25k	6.05	0.22	6.07	0.26	5.98	0.21	6.00	0.21
1.6k	5.69	0.23	5.72	0.24	5.63	0.29	5.62	0.22
2k	4.63	0.21	4.73	0.18	4.64	0.16	4.64	0.20
2.5k	3.68	0.20	3.86	0.15	3.80	0.16	3.78	0.14
3.15k	2.93	0.11	3.07	0.11	3.04	0.11	3.03	0.11
4k	2.30	0.09	2.45	0.09	2.42	0.11	2.42	0.12
5k	1.71	0.07	1.83	0.07	1.80	0.07	1.82	0.06
$(100–3150)_{\text{ave}}$	6.75	0.58	6.75	0.60	6.63	0.53	6.53	0.51

3. Measurement results

The measurement results have been divided into two categories. The first of these are the values of the determined sound insulation spectrum for the four above-mentioned variants on the basis of which weighted apparent sound reduction index R_w and adaptation terms C and C_{tr} were determined. The second category is the uniformity analysis of sound pressure level distribution in both rooms and the reverberation time in the receiving room determined by the spread of the measurement results based on the standard deviation. These values were also used to calculate the uncertainty of measurements.

Tabular summary of 1/3 octave sound reduction spectra with R_w, $C_{1000–3150}$, and $C_{tr,\,1000–3150}$ indicators for different variants of distribution of diffusers are presented in Table 1 and Fig. 3.

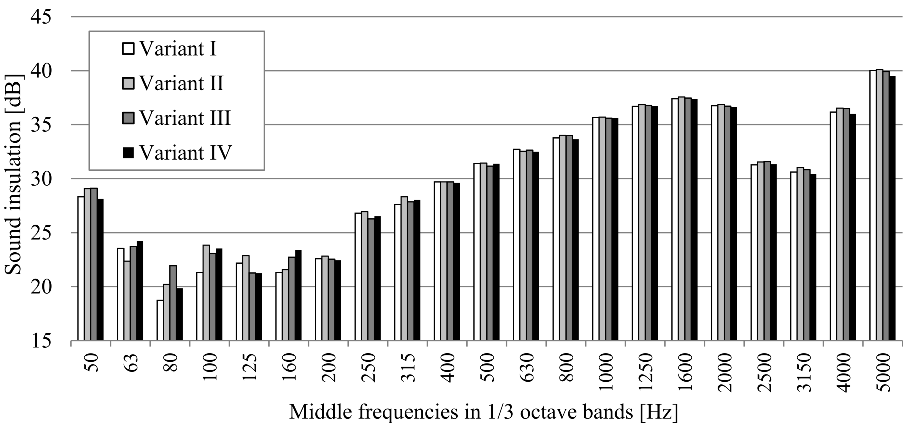

Fig. 3. Results of sound insulation measurements in 1/3 octave bands for the tested variants of distribution of diffusers.

The variability of the measurement results of the sound pressure level in the receiving room is shown in Fig. 5 using the standard deviation.

Summary of the measured length of the reverberation time T_{30} in the receiving room is shown in Table 2 and Fig. 6. In addition, the average value for the frequency range used in the calculation of R_w (100–3150 Hz) was calculated. Figure 7 shows the extended uncertainty $u_{c(95)}$ of the reverberation time in 1/3 octave bands for variants I to IV of receiving room adaptation.

The results of acoustic insulation measurements presented in Table 1 and Fig. 3 show a high similarity, especially in the area of higher frequencies, with

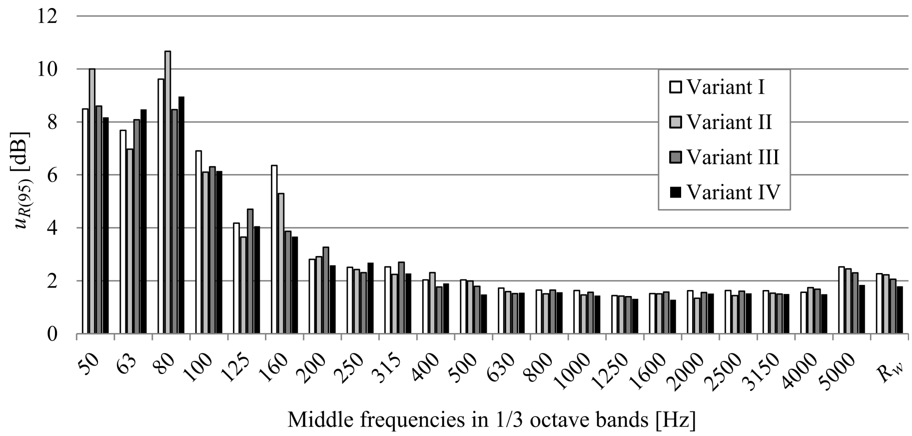

Fig. 4. Uncertainty extended $u_{c(95)}$ of sound insulation in 1/3 octave bands and uncertainty of R, C, and C_{tr} in variants I to IV of the receiving room adaptation.

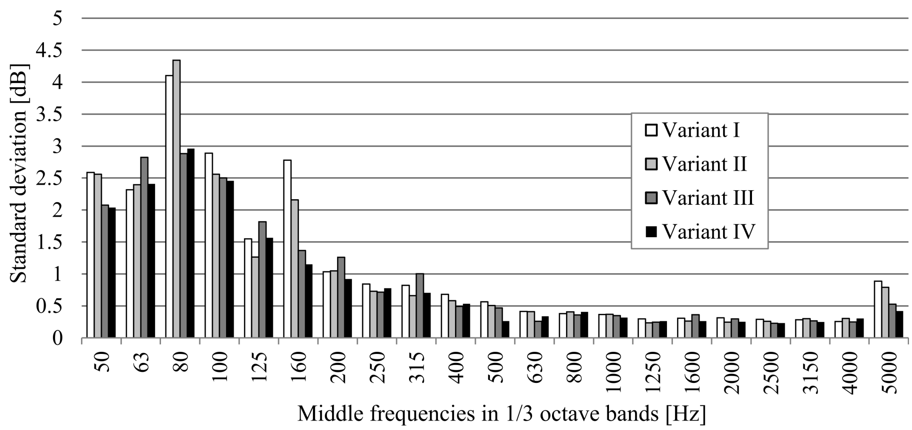

Fig. 5. Standard deviations of the sound pressure level measurement results in the receiving room in the 1/3 octave band for variants I to IV of the receiving room adaptation.

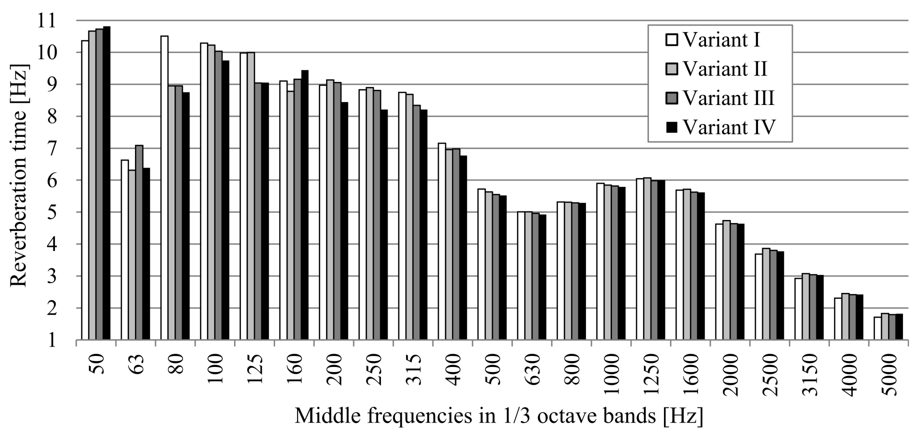

Fig. 6. Results of reverberation time T_{30} measurements in 1/3 octave bands for the tested variants of distribution of diffusers.

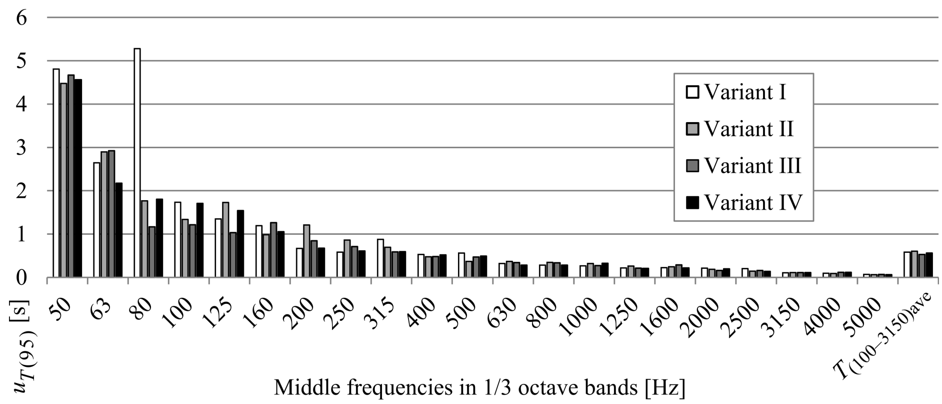

Fig. 7. Uncertainty expanded $u_{c(95)}$ of reverberation time T_{30} in variants I to IV of the receiving room adaptation.

a slightly greater variation in the lower bands. The R_w values are the same and the average uncertainty of measurements in the band of this indicator in subsequent variants along with the increase in the amount of scattering materials decreases slightly. In the low frequency bands, in particular 80 and 160 Hz, the results are significantly larger than in the remaining range (Fig. 4), but also with the tendency of decreasing with increasing amount of diffusing materials. Sources of this variability can be noticed in unevenness in the distribution of the sound pressure level in these bands in the receiving room (σ_{L_2}, Fig. 5), also with a downward trend in subsequent variants. The reverberation time values are strongly scattered especially in the 80 Hz band, especially in the empty room. However, after the first adaptation (Variant I) stabilisation of these results was observed. There were also significant differences between the results at different sound source settings, but without a noticeable tendency.

On the basis of the results presented in Table 1 and Fig. 3, it is difficult to indicate any influence of the application and method of distribution of diffusing materials in the receiving room on the determined values of sound insulation. The first differences are observed when trying to analyse the standard deviation of the sound pressure level measurement results in the receiving room (Fig. 5). In the case of bands with centre frequencies of 80 and 160 Hz, in the first two stages of adaptation there is a significant variability of obtained results, which directly affects the expanded uncertainty acoustic insulation (Fig. 4). In other bands, these differences are no longer noticeable.

Further differences can be noted by analysing the length of reverberation time in the receiving room, which is reduced in the 80 Hz band after the first part of the adaptation. Subsequent versions of adaptation, however, do not bring major changes. At the same time, based on the observation of uncertainty, the extended measurements of reverberation time can be stated that in the 80 Hz band the uniformity of reverberation time in the whole acoustic field has definitely improved. In the remaining bands, the differences in results are unfortunately not so spectacular.

4. Conclusions

Research on the impact of receiving room acoustic adaptation in the coupled reverberation rooms on the results of sound insulation measurements from airborn sound insulation were carried out in this work. In four subsequent variants, the amount and distribution of the diffusing materials was increased expecting the reduction of the reverberation time and the equalisation of its frequency response.

With an increase in the number of diffusing elements, a slight decrease in the reverberation time from the average value of 6.75 s in the empty room to 6.53 s in the room with the maximum adaptation variant, with a slightly flatter and therefore more favourable characteristics was observed. There is also a slight decrease in the variability of the results of both reverberation time and sound pressure level, which at the same time influenced adequately the measurement results of acoustic insulation. The R_w measurement uncertainty decreased from 2.3 to 1.8 dB. However, the above changes (greater homogeneity of results) do not influence the measurement results of airborne sound insulation in terms of quantity or quality. All indicators have the same values in all four variants.

It can therefore be concluded that the acoustic adaptation of the receiving room did not affect the measurement results of the basic acoustic insulation indicators, but improved the uniformity of the frequency domain of both the reverberation time and sound pressure level. This is particularly evident in the range of medium and higher frequencies (above 200 Hz), which is manifested by a noticeable reduction in measurement uncertainty.

It is worth noting that the above results are based on relatively large measurement series (40 measurements in each). However, with shorter series, it cannot be excluded that a larger spread of results will also affect quantitative changes in the R_w index.

Acknowledgments

The project was financed by the Polish Ministry of Science and Higher Education (project No. 16.16.130.942/KMiW).

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