An Experimental Investigation of Acoustic Parameters of Reverberant Chambers for a Measurement of Sound Insulation of Building Elements

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ABSTRACT: The report deals with a task of investigation and adjustment of acoustic parameters of the reverberant chambers of newly built laboratory for a measurement sound insulation properties of building elements in accordance with requirements of LST EN ISO 140-1, 20 140-2, 140-3 standards just recently adopted in Lithuania. Repeatability value r of the measurement of sound reduction index of plastic window estimated from statistical data obtained under repeatability conditions proves sufficiently high measurement precision.

KEYWORDS: sound insulations, sound reduction index, loudspeaker optimal position.

NOTATION

V_r – volume of the receiving room;
V_s – volume of the source room;
μ_{iA}, μ_{iB}, μ_{iC}, μ_{iD} – the mean of level differences at ith 1/3 octave frequency band for combinations A, B, C, D of loudspeaker positions appropriately;
S_{jA}, S_{jB}, S_{jC}, S_{jD} – the sum of S_j of squares of deviations for A, B, C, D combinations of loudspeaker positions appropriately.

1. INTRODUCTION

The weakest places in the building with respect of external noice reduction are windows and doors. To assure the noise level lower than allowable by regulations it is needed already before onset of project to evaluate environmental noise level, that to choose windows and doors with required value of noise reduction indices. Thus it is evident how it is important to measure noise reduction index of building elements with required accuracy. The main requirements for physical dimensions of laboratory rooms and its acoustic parameters, accuracy of measuring means are formulated in the standards [1, 2, 3]. Unfortunately the description of some procedures is insufficiently detail and the sequential order of adjustment steps is not clearly revealed as fully as it is done for example in the ASTM standard [4] on our mind. Thus it was necessary refer on own sense making plans for sequence of experiments and assessing the test results.

The main goal of this work experimentally to check conformance of acoustical parameters of test facilities to the requirements prescribed by appropriate standards and to make an assessment of measurement precision.

2. INVESTIGATION

2.1. The test facility description.

The general view of newly built acoustic laboratory for sound insulation measurements of building elements is show in two cross-sections (see Fig. 1). How it could be seen from Fig. 1 the laboratory consists from two adjacent rooms separated by the double filler concrete wall and room for measuring means. The geometry of the rooms was confined physically and financially. It was chosen sub regular form of rooms carried out by constructing the ceiling of rooms in the form of descending steps from sidewalls toward the filling wall. In the filling wall there are prepared two openings e.g. one for windows (1500 mm × 1250 mm) and the second one for doors (950 mm × 2100 mm). It is foreseen that in the case of testing one of above mentioned specimens another opening is to be closed by acoustically insulating and reflecting materials assuring insulation equivalent to the insulation of concrete filler wall. It is possible of course to pull down the filling wall and to build partition to be tested. The volumes of the rooms are V_r=68,5 m^3 and V_s=79,9 m^3 while the minimum required volumes could be 50 m^3 [1]. A difference in room volumes is about 14% with respect of bigger volume while at least 10% difference is recommended [1].

To provide the measurements the following equipment units were used:

Real time spectra analyzer of the type 2800B – Larson&Davis;
Microphone scanner – local product;
Microphone capsule 2560 – Larson&Davis;
Preamplifier PRM 900 C – Larson&Davis;
Power amplifier with 20 band equalizer – local product;
Omnidirectional loudspeaker made in the form of dodecahedron – local product;
Calibrator CAL 200 – Larson&Davis.

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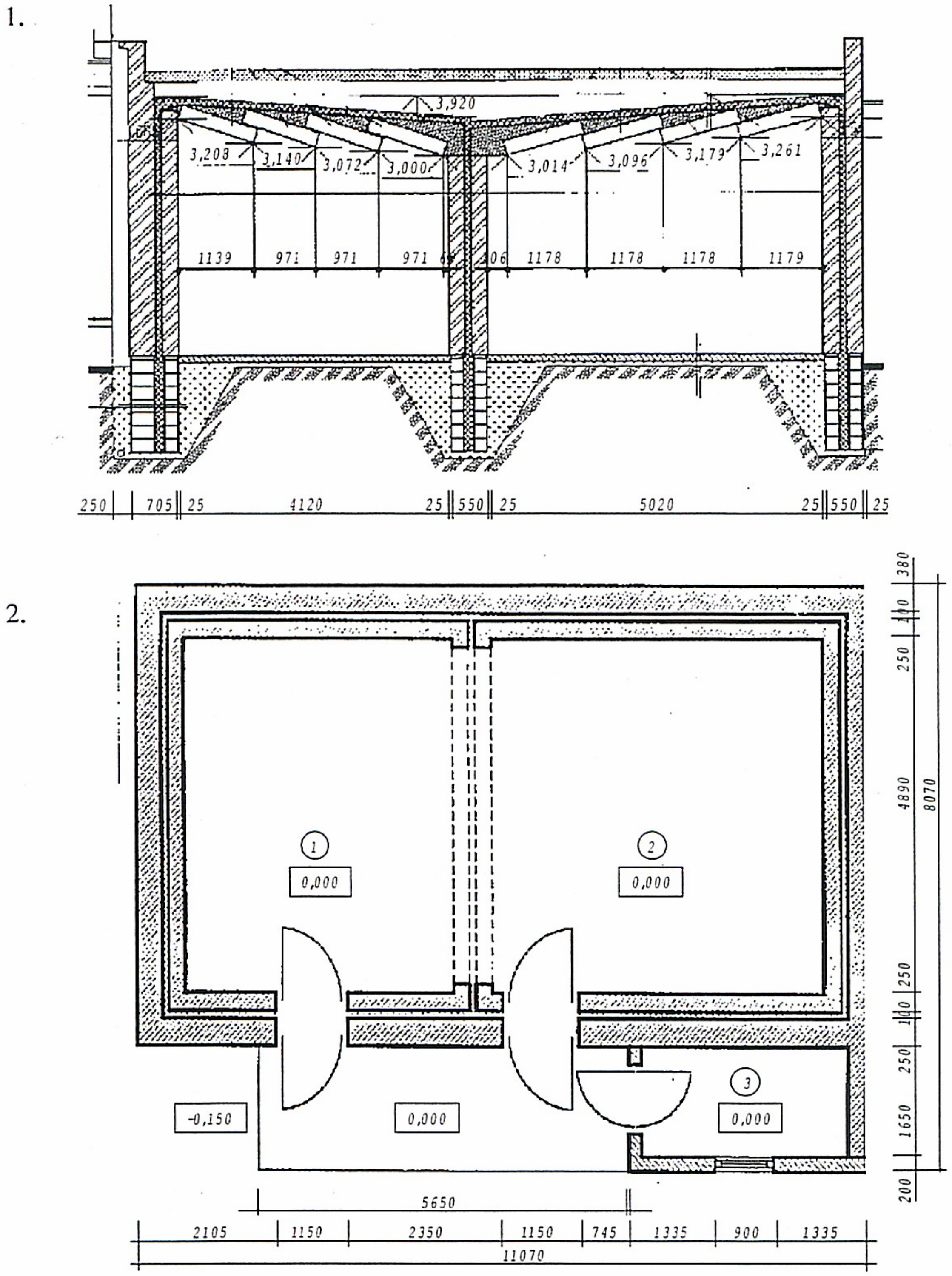

Fig. 1. The general view of construction of the laboratory for sound insulation measurements of building elements
1) vertical – longitudinal cross-section
2) horizontal cross-section

2.2. Reverberation time adjustment.

The one of the acoustic parameter of the reverberant chambers is reverberation time T_r, which as stated in [1] under normal test conditions should not be excessively long or short. The both openings in the filler wall were closed by the sandwich of glass fiber and particle boards the side surface flushing with the face of the filler wall the T_r to be measured in each in room. Let designate conditionally the left chamber (see Fig. 1) with a smaller volume as receiving room and adjacent bigger one as source room. Reverberation time was measured in 1/3 octave frequency bands with central values from 100 Hz up to 3150 Hz utilizing special auto storage mode of RT 2800 B allowing to store decay curves of the sound level in above mentioned frequency bands simultaneously. Spatially averaged values of T_r were obtained by averaging the decay curves measured at six points in the room space, utilizing block-averaging function of an analyzer. T_r values in all frequency bands measured in empty rooms (see Fig. 2: 1, 2) significantly exceed the recommended [1] which could be found from inequality:

$$1\ \text{s} \le T_r \le 2 \cdot (V/50)^{2/3}\ \text{s}. \qquad (1)$$

which defines limits of T_r values at low frequencies. For the volumes of the rooms investigated it should be within limits 1 s. $\le T_r \le$ 2,4 s. and 1 s. $\le T_r \le$ 2,734 s. corresponding the receiving and source room appropriately. Thus for the purpose of T_r reduction at low frequencies the four low frequency absorbers were randomly fixed on the walls of each room. The absorbers comprise the wooden frame (950 × 650 × 50) mm closed by the 4 mm thick plywood of the same lateral dimensions with the fiberglass mat inserted between the wall and plywood. The effect of that measure you can see in Fig. 2. curves 3, 4. It can be seen that reverberation time at low frequencies decreased noticeably but not in such degree to satisfy inequality (1). To achieve desirable values throughout the whole frequency range it was necessary additional number of low frequency absorbers to be installed, number of diffusers to be hanged up on the ceiling and put on the floor and some absorbers in the form of fiberglass boards to be placed on the floor. Finally eight low frequency absorbers were fixed in receiving room and five in the source room, three diffusers hanged up on the ceiling in each room. To reach desirable value of T_r at low frequencies and to avoid standing waves two diffusers (2500 × 1200) mm made from plasterboard were put on the floor at the some angle against the sidewall surface in each room. Finally obtained T_r frequency dependences in each room are shown on Fig. 2: curves 5, 6.

2.3. The background noise level.

The background noise level in the receiving room is one of significant acoustic parameter of the laboratory conditioning the measurement possibility of noise reduction index of high performance element like the solid wall for instance. As it is stated in [3] the background noise level should be at least 6 dB (preferably more than 15 dB) below the level of signal and noise combined. The background noise level in the receiving room was measured at the six points in the space by positioning microphone with an aid of remotely controlled scanner, allowing to stop rotation of traverse at each 30° angle. The traverse rotation plane was inclined in angle of 30° with respect of floor surface. The microphone traced the circle of 1,2 m in radius.

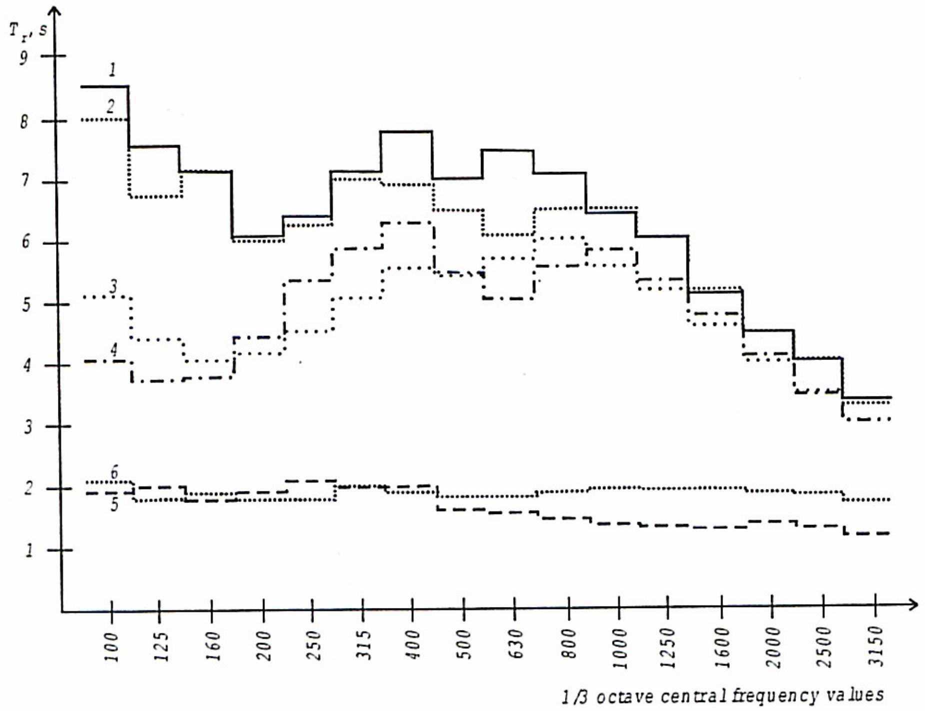

Fig. 2. The reverberation time frequency dependence
1, 2 – an empty receiving and source room appropriately
3, 4 – receiving and source room with four resonance absorbers installed in each room
5, 6 – receiving and source room the final adjustment provided

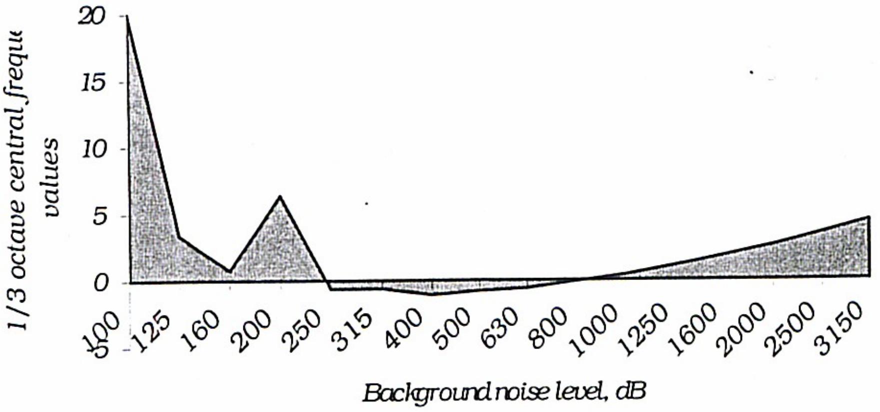

Fig. 3. Background noise level in the receiving room

The two peaks of background noise level at 100 Hz and 200 Hz could be seen on the diagram (Fig. 3). The origin of this noise is the electric transformation station standing at the left of laboratory (see Fig. 1). The tonal noise of 50 Hz harmonics propagates throughout the ground and foundation of the room, because there are no other mechanical contacts between transformation station and laboratory construction. However such sufficiently low level of noise could be tolerated because of big reserve of power of noise amplification – loudspeaker system which can produce overall level in the frequency range 100 Hz – 3150 Hz over 100 dB. The background noise level at the rest of frequency range is extremely low, what should potentially serve for obtaining of good measurement results.

2.4. Optimization of loudspeaker position

The main condition to measure insulation properties of the test object with minimum errors is to create sound field, which is incident on the specimen as diffuse as possible. Field diffusivity depends from geometry of chambers, directivity of loudspeaker, position and number of diffusers installed. There exist methodical uncertainty [3] solving this task from point of view in what sequence adjustment procedures to be done. As it is recommended [1] the number of randomly distributed diffusers should be defined by increasing number of diffusers in consecutive order until the measured sound reduction index $R(f)$ will take minimum and not varying value, indepdently from further increment of diffusers. The other way to achieve maximum diffusive field is positioning of loudspeaker in the source room with respect of already installed diffusers [3]. It was chosen this way to create maximum achievable diffusivity because number of diffusers is limited by the minimum allowable distances between rotating microphone and surfaces of diffusers. First of all it was checked the directivity of loudspeaker in accordance with procedure described in [3]. The values of directivity indices obtained were much smaller than it allows appropriate limits in different frequency bands. So it was proved that loudspeaker radiates uniformly and omnidirectionally. The second thing what it was done the opening for windows in filler wall was opend and plastic windows was installed. A number of loudspeaker positions to be investigated could be defined by expression.

$$m=152\ V_s^{2/3}. \tag{2}$$

In our case m=8. According to the guidelines [3] for finding optimum positions it were measured difference D between time and spatially averaged levels in the source and receiving rooms for each loudspeaker position. The standard deviation s_i of these differences for each one-third octave band with center frequency from 100 Hz to 315 Hz were calculated using following expression:

$$S_i = \left[\frac{1}{m-1}\sum_{j=1}^{m}\left(D_{ji}-\mu_i\right)^2\right]^{1/2}; \tag{3}$$

where $D_{i,j}$ – is the level difference for the j^{th} loudspeaker position at the i^{th} one-third-octave band.

μ_i – is the arithmetic mean of the differences in levels in the i^{th} one-third-octave band.

The number, N, of loudspeaker position to be used in practice is determined by the following conditions, – $N \geq 2$, $N \geq (s_i / \sigma_i)^2$, $N \geq \left(\sum_i s_i / 4{,}8dB\right)^2$ where σ_i is prescribed maximum standard deviation of the mean values for N loudspeaker positions from 100 Hz to 315 Hz. It is required that if 2N exceeds the number of loudspeaker positions m investigated, this number shall be increased from m to 2N. After the calculations were performed for m=8 loudspeaker positions it was determined from above inequalities that N=8 and m loudspeaker positions should be m=2N=16. At last the 17 feasible positions were investigated. The sum S_j of the squares of the deviations from the mean values at the six one-third-octave bands were calculated for each loudspeaker position as:

$$S_j = \sum_{i=1}^{6}\left(D_{ji}-\mu_i\right)^2. \tag{4}$$

Table 1. Difference in level D_{ij} values and statistical parameters

j \ i	1	2	3	4	5	6	S_j
	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	
1	30,8	27,2	28,4	23,2	23,8	28,8	5,4
2	33,4	29,8	27,6	23,8	24,3	29,4	21,5
3	32,1	30,1	27,2	22,8	23,8	27,6	14,3
4	31,3	27,4	28,8	23,8	26,2	29,6	13,5
5	30,2	28,6	27,2	20,1	24,3	26,5	11,2
6	34,5	27,5	30,2	22,4	23,3	29,6	24,6
7	31,1	28,9	27,9	20,2	22,3	28,3	7,7
8	28,6	29,2	31,6	22,6	24,8	28,7	11,2
9	30,2	28,3	28,1	20,9	24,7	30,5	4,3
10	25,3	26,5	33,0	18,4	24,2	29,6	51,2
11	31,7	27,2	29,6	20,0	25,5	27,5	11,3
12	30,1	28,9	28,0	22,7	24,6	30,6	6,0
13	28,8	30,7	28,3	21,8	24,0	30,2	9,1
14	26,7	28,3	31,4	20,9	23,1	27,9	18,5
15	27,4	30,4	29,4	21,6	21,3	28,6	18,1
16	26,4	25	28,0	19,6	22,7	28,7	30,3
17	30,6	28,2	28,4	20,7	24,8	29,3	2,3
μ_i	29,95	28,36	29,01	21,5	23,98	28,9	
S_i	2,49	1,48	1,66	1,56	1,19	1,12	

Table. 2. D_{ji}, S_{jg} values from A, B, C, D combination of loudspeaker positions

	j \ i	1	2	3	4	5	6	S_j
		100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	
A	1	30,8	27,2	28,4	23,2	23,8	28,8	4,06
	17	30,6	28,2	28,4	20,7	24,8	29,3	1,11
	9	30,2	28,3	28,1	20,9	24,7	30,5	1,81
	$\mu_{i,A}$	30,53	27,90	28,30	21,60	24,43	29,53	
	$S_j = \sum_{i=1}^{6} (D_{j,i} - \mu_{i,A})^2$				$S_{j,A} = \sum_{j=1}^{3} S_j =$			6,98
B	1	30,8	27,2	28,4	23,2	23,8	28,8	3,66
	12	30,1	28,9	28,0	22,7	24,6	30,6	1,32
	9	30,2	28,3	28,1	20,9	24,7	30,5	2,33
	$\mu_{i,B}$	30,37	28,13	28,16	22,27	24,37	29,97	
	$S_j = \sum_{i=1}^{6} (D_{j,i} - \mu_{i,B})^2$				$S_{j,B} = \sum_{j=1}^{3} S_j =$			7,31
C	9	30,2	28,3	28,1	20,9	24,7	30,5	0,46
	12	30,1	28,9	28,0	22,7	24,6	30,6	2,55
	17	30,6	28,2	28,4	20,7	24,8	29,3	1,45
	$\mu_{i,C}$	30,3	28,47	28,17	21,43	24,7	30,13	
	$S_j = \sum_{i=1}^{6} (D_{j,i} - \mu_{i,C})^2$				$S_{j,C} = \sum_{j=1}^{3} S_j =$			**4,47**
D	1	30,8	27,2	28,4	23,2	23,8	28,8	2,85
	17	30,6	28,2	28,4	20,7	24,8	29,3	5,37
	12	30,1	28,9	28,0	22,7	24,6	30,6	2,24
	$\mu_{i,D}$	30,50	28,10	28,26	22,20	24,40	29,56	
	$S_j = \sum_{i=1}^{6} (D_{j,i} - \mu_{i,D})^2$				$S_{j,D} = \sum_{j=1}^{3} S_j =$			10,46

The measured and calculated values are presented in table 1. The four loudspeaker positions j=1, 9, 12, 17 for which values S_j are smallest were selected from all investigated loudspeaker positions. Further according to the description [3] the combination of q positions from those with minimum S_j values (see table 1) should be chosen and the sum S_{jq} of the S_j for each combination is to be calculated. Here exist an uncertainty what does it mean the "mean values". Is it the μ_i value calculated from j=17 loudspeaker positions or is it the mean values calculated from the data of each combination separately. According our mind it should be calculated the new mean values for each combination of q positions and the sum of the squares of deviation S_{jg} from newly determined mean values should be calculated. The reason we can find in it is that newly calculated mean values should better correspond the mostly successful positions in respect of better diffusivity of the acoustic field in the room. In other words the new mean values are less affected by the unsuccessful loudspeaker positions. Thus it was chosen four combinations with three positions from four positions of loudspeaker. It were chosen following combinations:

A) j= 1, 17, 9
B) j= 1, 9,12
C) j= 9, 12, 17
D) j= 1, 17, 12

The results of calculations are presented in the table 2.

It can be seen from table 2 that combination C should be chosen as optimum because $S_{j,C}$=4,47 is the smallest from total collection of combinations.

2.5. Verification of repeatability values *r* of sound reduction index *R(f)*.

The six complete tests comprising 16 frequency bands on the same specimen (plastic window) were carried out under repeatability conditions according to the guidelines described at item 5.1 of [2] using an optimal combination of loudspeaker positions (combination C). The repeatability values r for all frequency bands were calculated by expression:

$$r = 2{,}8\sqrt{s_r^2}\ ; \qquad (5)$$

where s_r is repeatability standard deviation calculated from experimental data. These repeatability values considered to be satisfactory if the standard deviation s_r for all 16 frequency bands satisfies inequality $s_r \leq m r_{inter}$, where m is a factor equal 0,68 for 6 tests [2], r_{inter} is repeatability values determined in the interlaboratory test on the similar specimen given in table A1 [2]. All calculated statistical data are given in table 3.

It can be seen from the table 3 that inequality $s_r \leq m r_{inter}$ is satisfied in all frequency range and repeatability value r could be considered to be satisfactory.

Table 3. Statistical data for varification of repeatability value r

f, Hz	s_r	mr_{inter}	r_{inter}	r
100	0,16	3,06	4,5	0,45
125	0,12	2,72	4	0,34
160	0,24	2,38	3,5	0,67
200	0,27	2,38	3,5	0,76
250	0,30	1,70	2,5	0,84
315	0,25	1,70	2,5	0,70
400	0,34	1,36	2	0,95
500	0,19	1,36	2	0,53
630	0,22	1,02	1,5	0,62
800	0,17	1,02	1,5	0,48
1000	0,23	1,02	1,5	0,64
1250	0,32	1,02	1,5	0,90
1600	0,19	1,02	1,5	0,53
2000	0,16	1,02	1,5	0,45
2500	0,17	1,02	1,5	0,34
3150	0,09	1,02	1,5	0,25

CONCLUSIONS

At the result of experimental investigation of acoustic parameters of the reverberation chambers of newly built laboratory for a measurement of sound insulation properties of building elements it was determined that reverberation time values in all one-third-octave frequency bands exceed recommended one, showing the necessity of its correction. After a series of means being introduced and reverberation time being adjusted until required values, the procedure for finding optimal loudspeaker position was carried out and here in the article the stages of that process are revealed visually and the optimal positions were determined. The calculated repeatability values r for each one-third-octave frequency band (100÷3150) Hz from number of complete tests being carried out proves sufficient precision of measurements.

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