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Sound insulation performance of cube-shaped enclosures

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Abstract The subject of the research described in the article are the sound insulating properties of a cube-shaped enclosures, the walls of which are made of plates of homogeneous materials and two-layer baffles. As an enclosure for an omnidirectional sound source imitating a noisy machine or device, a prototype test stand for testing the acoustic properties of materials and enclosures was used. The three tested variants were enclosures with walls made of plastic plates, such as polyethylene, solid polycarbonate, and plates in the form of rigid polyethylene foam. The fourth variant was an enclosure with walls made of sandwich baffles in the form of a steel plate with a rubber layer glued on. Calculations of the effectiveness of the enclosure were carried out using the previously developed theoretical calculation model for insertion loss (IL). The obtained results were related to the IL obtained in the course of experimental tests. The research showed slight discrepancies between the calculations and the measurement results for almost all tested materials in the entire frequency range (100-5000 Hz), with the exception of rigid polyethylene foam, for which the discrepancies were relatively the largest in the lower frequency range, i.e. below 400 Hz. Research has shown that the best sound insulation performance was achieved for an enclosure with two-layer walls.

Keywords: acoustical enclosure, insertion loss, sound transmission loss, sound insulation

1. Introduction

The basic elements used in the construction of anti-noise solutions are baffles, which is why the acoustic properties of the materials they are made of are of great importance. Among many different types of baffles, including layered ones, with sound-absorbing and insulating properties, single baffles with sound-insulating properties are also used. Baffles of this type are used, among others, in sound insulating enclosures [1-7] and sound-absorbing and insulating ones [8-10].

The main purpose of the research was to calculate the insertion loss of two cubic sound insulating enclosures, built of five identical walls, made of polyethylene and polycarbonate plates, using a theoretical model proposed in previous studies described in [11]. This was a continuation of the study of cubic enclosures with walls made of steel, aluminum and plexiglass plates. This article also describes an attempt to use the calculation model for insertion loss proposed in [11] for two consecutive enclosures, built of non-standard baffles. The first set of five identical boards was a material of relatively high thickness (50 mm) and low density (94 kg/m^3), which was XPE rigid polyethylene foam, with which an additional difficulty in calculating the insertion loss of the enclosure was the lack of material data of the plates, such as, the Young module, the Poisson's ratio and the loss factor. The second case concerned the tests of the enclosure with walls, not single homogeneous ones, as before, but made of two-layer baffles, consisted of steel and rubber plate. All the results of the insertion loss calculations were related to the experimental tests, for which this parameter was determined on the basis of the difference in the sound power level of an unenclosed and an enclosed omnidirectional sound source imitating a noisy machine or device.

2. Experimental setup and material data

Acoustic tests were carried out by using a prototype test stand for testing acoustic properties of materials and enclosures, which was described in [12, 13]. An enclosure with a set of five identical walls measuring 0.7 × 0.7 m was tested for different baffle types, which of material data was shown in Table 1.

Experimental tests were carried out for four variants of the sound insulating enclosure. Three variants were enclosures with walls made of plastic plates, such as polyethylene (Fig 1a) and solid polycarbonate (Fig. 1b), as well as plates in the form of XPE rigid polyethylene foam (Fig. 1c). The XPE plate was a material in the form of chemically cross-linked foam with a closed-cell structure. The fourth variant was an enclosure with walls made of two-layer baffles in the form of a steel plate, to which a rubber plate was glued (Fig.1d).

Figure 2 shows an enclosure constructed with the use of a prototype stand for determining the acoustic properties of materials and enclosures, for one of the analysed variants - panels of XPE foam.

Table 1. Material data of the tested enclosure walls.

Quantity	Symbol	Unit	Value				
			Polyethylene	Polycarbonate	XPE foam	Steel	Rubber
Density	*r*	kg/m^3	950	1190	94	7850	1825
Thickness	*h*	m	0.010	0.006	0.05	0.001	0.003
Young's Modulus	*E*	GPa	1.4	2.3	N/A	207	0.006
Poison's Ratio	*n*	-	0.44	0.35	N/A	0.3	0.48
Loss factor	*h*	-	0.03	0.003	N/A	0.01	0.00075

a) b) c) d)

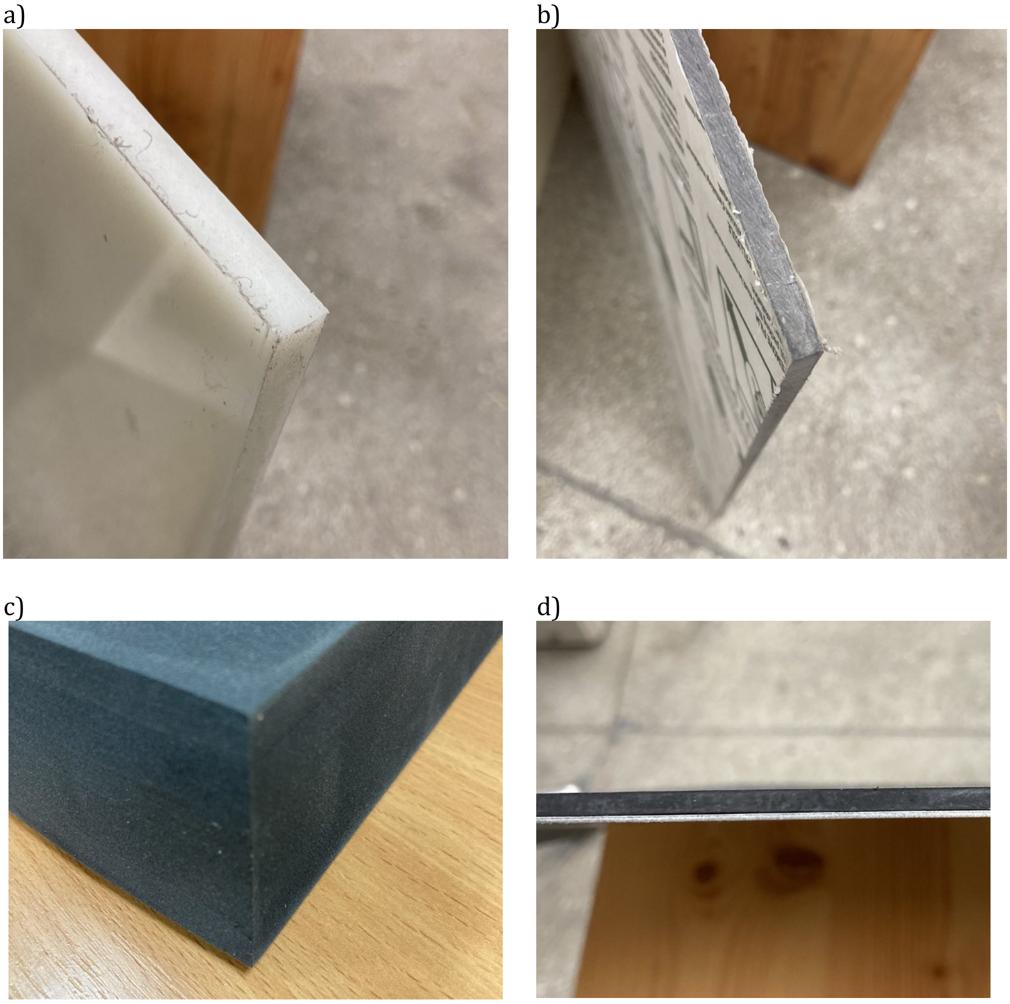


Figure 1. View of the tested enclosure walls: a) polyethylene, b) polycarbonate, c) XPE foam, and d) two-layer baffle consisting of rubber and steel.

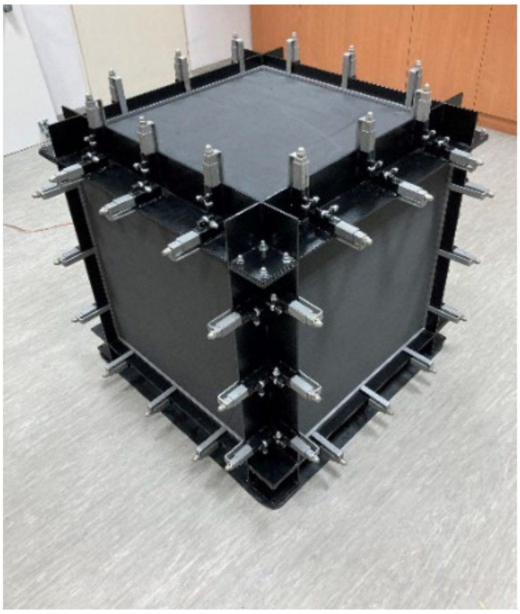


Figure 2. View of the enclosure with walls of XPE foam.

The insertion loss (IL) was calculated from the formula:

$$IL = 10\log\left(\frac{W_0}{W_E}\right) = L_{W0} - L_{WE}, \tag{1}$$

where: W_0, W_E are the sound power radiated by the unenclosed and enclosed omnidirectional sound source, respectively and L_{W0}, L_{WE} are the corresponding sound power levels.

Sound power level tests can be carried out using the survey method according to EN ISO 3746 [12, 14] or the precision one according to ISO 3745 [13, 15]. The survey method requires measuring the sound pressure level on a hemispherical measurement surface at 4 control points, while the precision method requires free field conditions and 20 measurement points.

Figure 3 shows the experimental test results of insertion loss for 1/3 octave band centre frequency of the analysed sound insulating enclosures.

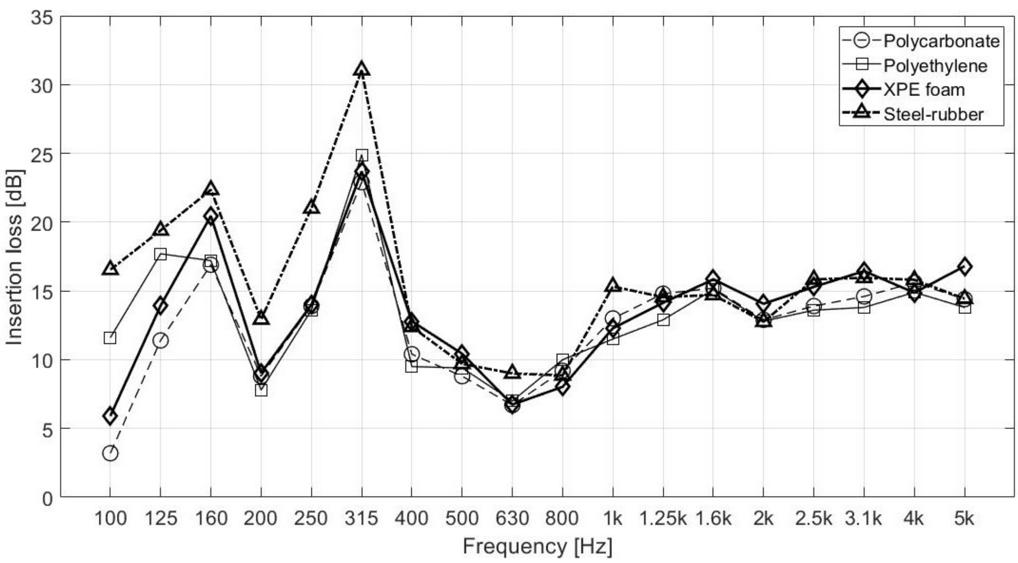


Figure 3. Insertion loss of enclosures of walls of materials: polycarbonate, polyethylene, XPE foam and steel-rubber.

3. Theoretical calculation insertion loss models of a sound insulation enclosure

The performance of enclosures with sound insulating walls, can be calculated from the simplified formula, proposed in [12]:

$$IL = 10\log\frac{\bar{\alpha}_{rand}}{10^{-0.1TL} + \mathrm{e}^{-0.23R_w}}, \tag{2}$$

where: TL is the sound transmission loss of the enclosure wall (dB), R_w is the single-number weighted sound reduction index of the enclosure wall (dB) and $\bar{\alpha}_{rand}$ is the random incidence sound absorption coefficient of bare enclosure walls [1, 12].

The weighted sound reduction index R_w is calculated from the sound insulation characteristic of the baffle, obtained from laboratory tests, according to the standard [16], or from the sound insulation characteristic of TL obtained from the calculation model. The best-known calculation model for the TL of a homogeneous baffle is the mass law, defined for the conditions of a diffuse sound field on both sides of the baffle as [1-4]:

$$TL = 20\log(f) + 20\log(m) - 47.5. \tag{3}$$

Formula (3) applies when the sound insulation of a baffle depends only on its surface mass m. The model of the mass law, which does not take into account the external dimensions of the baffle and the reduction of acoustic insulation associated with the occurrence of the coincidence phenomenon, was later improved by subsequent researchers, including Sharp [18] and Davy [17]. Combining of the Davy and Sharp models for determined frequency bands, proposed for homogeneous single baffles in [19], and for two-layer ones in [20], resulted in a better estimate of TL with respect to experimental tests.

Figure 4 shows the sound transmission loss calculated using the Davy-Sharp model for polycarbonate, polyethylene and steel-rubber baffles. Due to the fact that all material data needed for TL calculations were not known for the XPE foam baffle (Tab. 1), this parameter (shown in Fig.4) was determined on the basis of the mass law model given by the formula (3). The use of a simplified model to calculate the TL for an XPE baffle, with dimensions of 0.7 × 0.7 m, yielded results that are underestimated in the lower frequency region, which is visible in Fig. 4.

Based on the TL values for 1/3 octave band centre frequency (Fig.4), the single-number weighted sound reduction indices [16] of the tested enclosure walls R_w were calculated, as shown in Table 2.

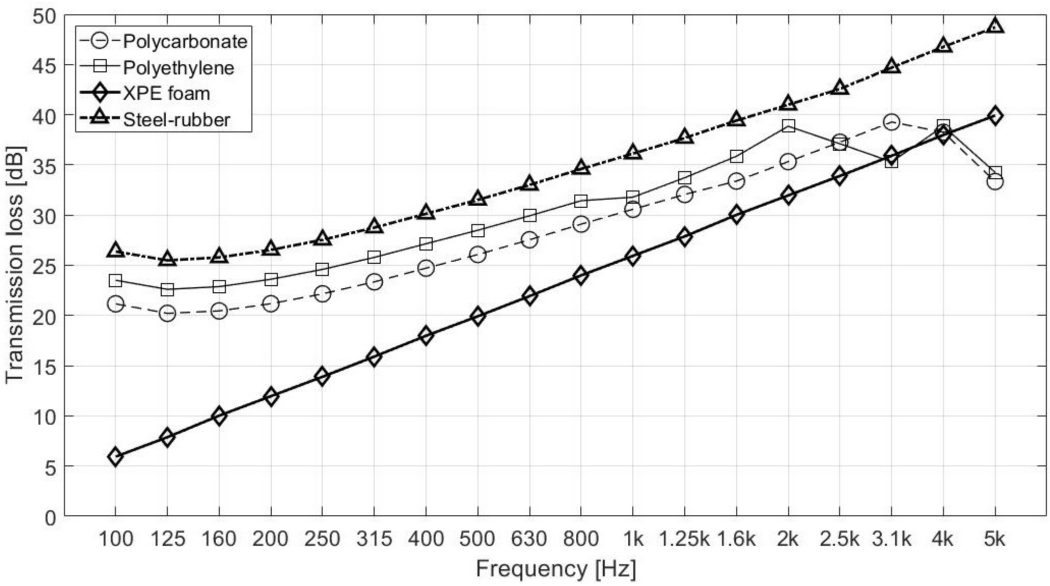


Figure 4. Transmission loss of baffles: polycarbonate, polyethylene, XPE foam and rubber-steel, obtained using calculation models.

Table 2. The single-number weighted sound reduction indices of the tested enclosure walls.

Material	R_w [dB]
Polyethylene	33
Polycarbonate	30
XPE foam	24
Steel-rubber	36

The results obtained by the calculation model for IL, given by formula (2), gave good results in relation to experimental tests of IL, for mid and higher frequencies [12]. However, it does not take into account the phenomenon of air resonance inside the cubic sound insulating enclosure.

Further research, involving more tested enclosure wall materials, developed a more accurate model that applies to the relevant frequency ranges depending on the eigenfrequency $f_{0,0,1}$ enclosure cavity. The insertion loss of a cubic enclosure made of homogeneous plates is determined from the following formula [11]:

$$IL = \begin{cases} 10\log[\cos(kd) - 0.32\rho h\omega\sin(kd)/\rho_0 c_0]^2, & \text{for } f \leq 1.5 f_{0,0,1} \\ 10\log\dfrac{\bar{\alpha}_{rand}}{10^{-0.1TL} + \mathrm{e}^{-0.23(R_w - 1.54\cdot10^{-7}\cdot(f_c)^2 + 0.0028 f_c - 12.2)}}, & \text{for } f > 1.5 f_{0,0,1} \end{cases} \tag{4}$$

where: ρ is the material density (kg/m^3), h is the material thickness (m), ω is the angular frequency (s^{-1}), ρ_0 is the air density (kg/m^3), c_0 is the speed of sound in the air (m/s), k is the wavenumber of sound, d is the distance of the top panel of the tested enclosure from the floor (m), $f_{0,0,1}$ is the first axial mode frequency of the enclosure cavity (Hz), f_c is the critical frequency of the wall of the enclosure (Hz) [1].

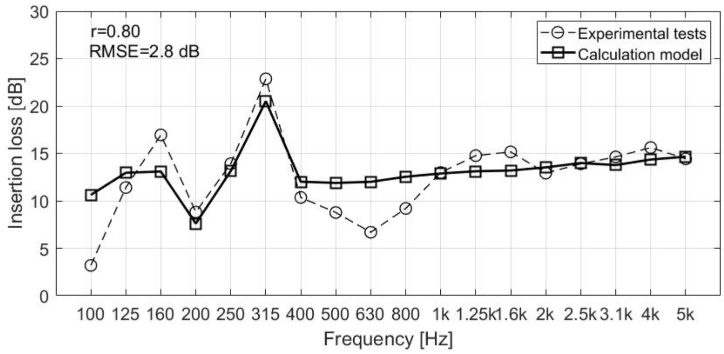
The application of the formula (4) gave good calculation results in relation to experimental tests for enclosures with walls made of materials such as steel, aluminium, plexiglass, polypropylene and gypsum [11].

4. Insertion loss calculation results and discussion

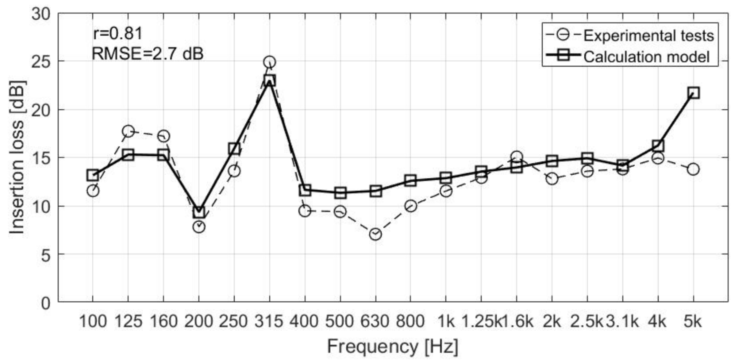
Insertion loss calculations for four variants of enclosures were referred to experimental tests in which the sound power levels of an enclosed and unenclosed sound source were determined using the survey method in a room with a volume of 79 m^3 (enclosures with walls made of plastic and XPE foam) and as part of previous studies, shown in [13] – using the precision method, in an anechoic chamber (enclosure with walls made of two-layer baffles). Insertion loss (*IL*) for enclosures with polycarbonate and polyethylene walls was calculated using formula (4). The results of the *IL* calculations in relation to the results obtained from the experimental tests are shown in Fig. 5. A good agreement of the results was obtained (linear correlation coefficient r = 0.8 and Root Mean Square Error, RMSE ≅ 3 dB), which is shown in Fig. 5a and 5b.

In the case of the enclosure with XPE foam walls, the only parameters that were known were the density and thickness of the plates, which were used for calculations of IL for the lower frequency range, $f \leq 1.5 f_{0,0,1}$. XPE foam is a specific material, with a very low density (ρ = 94 kg/m^3) in relation to typical homogeneous baffles used in anti-noise protection, and of a large thickness (h = 0.05 m). The use of formula (4) for the lower frequency range resulted in significant discrepancies of *IL* in relation to experimental tests (Fig. 2c), because the factor 0.32 in formula (4) was developed for baffles with much higher material density and much smaller thicknesses, amounting to (approx. 1 to 15 mm).

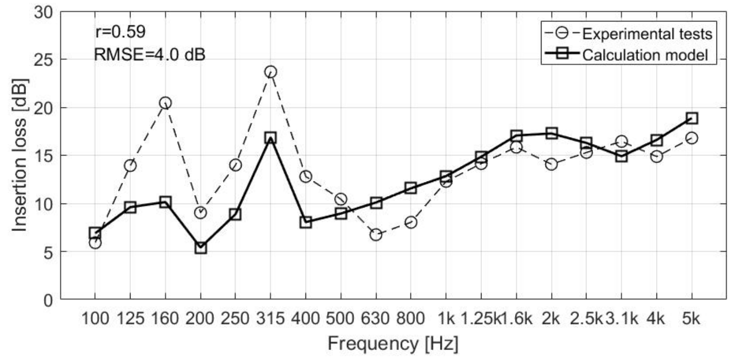
a)



b)



c)



d)

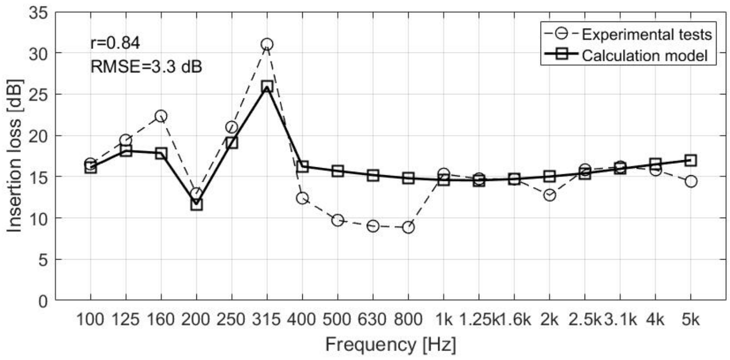


Figure 5. Spectral responses of the insertion loss of enclosures with walls of material: a) polycarbonate (0.006 m thick), b) polyethylene (0.01 m thick), c) XPE (0.05 m thick) and d) two-layer baffle consisting of rubber (0.003 m thick) and steel (0.001 m thick).

The discrepancies in the results in this frequency range translate into a relatively low value of the linear correlation coefficient r = 0.59 and a relatively high the value of the RMSE = 4 dB. In order to calculate the IL for the high-frequency range, without material data such as E, ν and η, necessary for the calculation of the coincidence frequency f_c, the model described by formula (2) was used for this purpose. The random incidence sound absorption coefficient of bare enclosure walls $\bar{\alpha}_{rand}$ (formula (2)) was calculated on the basis of the results of XPE foam tests carried out in the impedance tube, converting the physical sound absorption coefficient to reverberation one, using the airflow resistance, determined with laboratory measurement system Nor1517A, and using the AFMG SoundFlow software. Obtained results of IL were quite satisfying for the range of mid and higher frequencies (for $f > 1.5\ f_{0,0,1}$), as shown in Fig. 5c.

For the enclosure with two-layer walls, the formula (4) developed for enclosures with walls made of single homogeneous baffles was applied. For the lower frequency range, $f \leq 1.5\ f_{0,0,1}$, the product ρh in formula (4) was replaced by the surface mass of the baffle of two layers, i.e. the sum of the products of density and thickness for steel and rubber plate. For the frequency range $f > 1.5\ f_{0,0,1}$, it was necessary to use formula (2), because, the calculated frequency of coincidence f_c = 15726 [20] exceeded the frequency range for which formula (4) was developed for homogeneous baffles. The random incidence sound absorption coefficient of bare enclosure walls $\bar{\alpha}_{rand}$ (formula (2)) was calculated in the case of a two-layer baffle only for the material inside the enclosure, i.e. rubber. As a result of calculations of the IL of the two-layer walls enclosure, relatively small discrepancies were obtained in relation to the results obtained from experimental tests, as shown in Fig. 5d (r = 0.84, RMSE = 3.3 dB).

5. Conclusions

Verification of the IL calculation model for enclosures with walls made of homogeneous baffles for enclosures with walls made of polycarbonate and polyethylene showed good results in the form of small discrepancies in the results in relation to the results of experimental tests.

An attempt to calculate the IL for an enclosure with two-layer walls made of rubber and steel plates, using models developed for enclosures with single homogeneous walls, was successful. A fairly good convergence of the calculations with the results of experimental tests was obtained.

In the case of using a new material in the form of rigid XPE foam, which is not a typical material used in the construction of enclosures with walls of the type of single homogeneous baffles, and for which all the material properties necessary for the calculation of the enclosure IL were not known, satisfactory results were obtained for frequency range above 400 Hz. In this case, it was necessary to use a simplified model to calculate IL for this range. Similarly, due to the lack of all material data needed to calculate the TL of the wall, this parameter was calculated using the mass law, which does not take into account, among others, the external dimensions of the baffle, which is why the TL values for lower frequencies are underestimated. For frequencies lower than 400 Hz, the discrepancies were significant and amounted to about 5–10 dB, which affected the overall linear correlation coefficient of 0.59 and RMSE = 4 dB. However, the character of the curve obtained from the calculations for this frequency range is preserved with the curve obtained from experimental tests.

The spectral characteristics of the sound insulation performance of the tested enclosures with walls made of sound-reflecting materials have a similar curve. Research has shown that the best sound insulation performance is achieved for an enclosure with low-thickness two-layer walls. While the insertion loss of all enclosures is similar in the medium and higher frequency ranges, the enclosure with two-layer walls is distinguished by relatively high efficiency in the low frequency bands.

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Additional information

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

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