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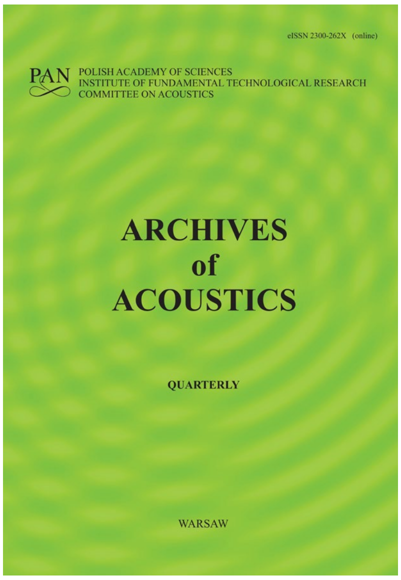

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Cube-shaped sound-insulating enclosures: Experimental tests and calculation models

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The research described in the article concerns sound-insulating enclosures used for sound sources imitating a noisy machine or device. It is a continuation of experimental tests and modelling studies conducted previously on a prototype test stand, in which the enclosure walls measured 0.7 m × 0.7 m. The main aim of the research was to estimate the acoustic efficiency of the enclosures through experimental testing on a new stand with walls measuring 0.55 m × 0.55 m, conducted under conditions similar to those found in an industrial facility. Tests conducted for five wall types of varying thicknesses, made of materials such as steel, aluminium, and plexiglass, enabled the development of a calculation model for insertion loss, which could be used on the basis of the material data for the enclosure walls. The model was validated during further experimental tests covering four additional material variants and a high correlation of the results was obtained. The influence of the calculation model used for the enclosure wall's transmission loss on the insertion loss result was also investigated. The results of the experimental tests and modelling studies were also compared to those obtained for a larger enclosure made of the same wall materials. The research described in the article may have practical applications in the selection of walls of cube-shaped enclosures and in estimating their effectiveness in a cost-free manner, assuming that the appropriate material data is used in the calculations.

Keywords: acoustical enclosures, insertion loss, noise protection.

1. Introduction

Homogeneous sound-insulating baffles have a number of applications in noise protection solutions. They can be used individually as shields or wall elements of acoustic barriers, or as walls of sound-insulating enclosures, usually designed to completely or partially isolate excessively noisy machines or devices (Barron, 2003; Ver, Beranek, 2006; Pawełczyk, Wrona, 2022; Min-Chie, 2012). The basic parameter determining the effectiveness of an acoustic enclosure is insertion loss (IL). This parameter can be determined experimentally, based on the difference in sound power levels between the unenclosed and enclosed sound sources, or using computational models, such as SEA (Nieradka, Dobrucki, 2018; Kim *et al*., 2014; Lei *et al*., 2012; Ming, Pan, 2004), or numerical methods (Zhou *et al*., 2011; Agahi *et al*., 1999). Selecting the proper material for an enclosure wall has a significant impact on its effectiveness, however, this is often dependent on economic and functional factors. The sound-insulating properties of a single baffle can be determined in a laboratory, but this approach cannot take into account all the factors that influence its final resistance to sound transmission, such as the mounting method being identical to the intended one in a specific enclosure, external dimensions of the panel other than those resulting from the dimensions of the laboratory's measurement window, and sealing method, etc. In order to estimate the sound insulation of a baffle with specific dimensions, calculation models (Kosała *et al*., 2020a) can be used, with the accuracy dependent primarily on the material data used, which in reality may differ slightly from the commonly known and typical ones given in the literature. To test the effectiveness of material and construction solutions for baffles and enclosures, a prototype test stand was proposed within the framework of previous research, the main element being a heavy steel frame with the possibility of attaching baffles constituting the enclosure walls (Kosała *et al*., 2020b). In addition to experimental tests of the effectiveness of an enclosed omnidirectional sound source imitating a noisy machine or device, a computational model has been developed that can be used to estimate the spectral characteristics of insertion loss of a sound-insulating enclosure without any cost (Kosała *et al*., 2020c; Kosała, 2022; Kosała, 2023). The experimental tests and modelling studies conducted so far concerned specific dimensions of the enclosure walls (0.7 m × 0.7 m), resulting from the developed test stand. As a continuation of this research, a smaller frame was developed, which enables the attachment of enclosure wall panels measuring 0.55 m × 0.55 m. The effectiveness of such cube-shaped sound-insulating enclosures, both experimental and model-based, is the subject of this article. A calculation model for the insertion loss of enclosures made of five material sets of different thicknesses, such as steel, aluminium and plexiglass, was proposed and validated by further experimental studies on another four material sets. This model is a function of parameters related, among others, to the sound-insulating properties of the walls of the enclosure in question, such as transmission loss (TL) and the single-number weighted sound insulation index of the wall, R_w, determined on its basis. These parameters were determined from the model proposed in previous studies, which is a combination of the models developed by Davy and Sharp, in specific frequency bands, respectively lower and higher, as described in (Kosała, 2019). The influence of TL, determined using SoundFlow and Insul programs, on the IL calculation results was also verified with respect to the experimental tests. The IL spectral characteristics obtained from experimental tests of enclosures were compared for four variants of wall materials, identical for the enclosure under study and the previously tested larger one with wall dimensions of 0.7 m × 0.7 m.

2. Measurement setup

The enclosure is based on a steel frame in the shape of a cube, allowing the installation of five walls measuring 0.55 m × 0.55 m with the thickness 0.001-0.09 m (Fig. 1). The frame is placed on a rubber plate, which ensures good tightness of the enclosure from the bottom. Each of the tested walls is tightened, through a rubber seal, to the enclosure frame using 0.01 m × 0.01 m square steel frames and a set of 11 holdfast mechanisms, except for the upper wall of the enclosure, which is attached using 12. The lower sides of the four walls, mounted vertically to the frame, are pressed against the frame using two holdfast mechanisms and a flat steel bar. This clamping solution allows the cubic shape of the enclosure cavity, measuring 0.55 m × 0.55 m × 0.55 m, to be maintained. Inside the enclosure, a loudspeaker is placed centrally on the floor (Fig. 1).

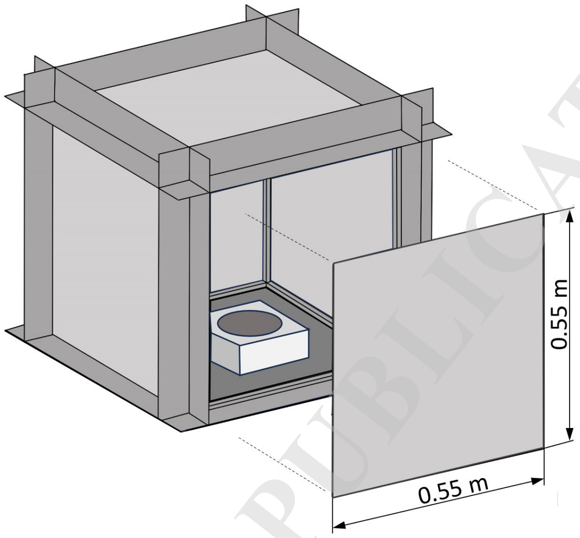


Fig. 1. Conceptual sketch of the enclosure in the form of a frame, loudspeaker and five walls.

Figure 2 shows the view of the enclosure frame with a loudspeaker (a) and the enclosure with steel walls (b). Acoustic tests were carried out in a room with a capacity of 79 m^3. The signal in the form of pink noise, generated in the Audacity program by an audio interface (EDIROL UA-5) and amplifier (Bruel & Kjaer 2716-C), was fed to a sound source. A SVAN 945A sound level meter was used to measure sound pressure levels on a hemispherical measurement surface, to determine the sound power levels of the source with and without the enclosure.

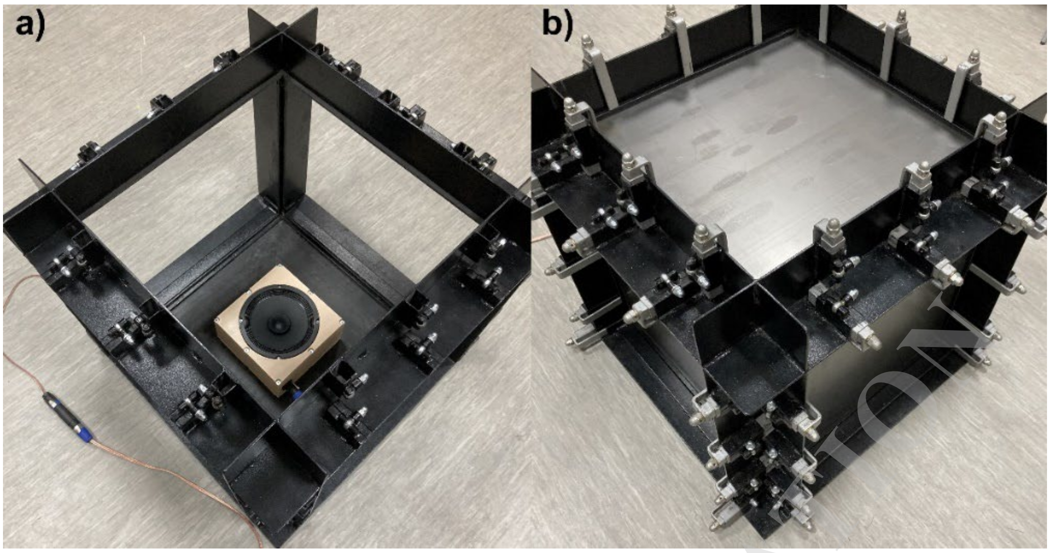


Fig. 2. View of the enclosure frame: a) without the walls, b) with steel walls installed.

For this purpose, the survey method was used in accordance with the standard (PN-EN ISO 3746, 2011), taking into account the correction factor for background noise K1 and the environmental correction factor K2. The surface sound pressure level was averaged from the results obtained from measurements carried out at 4 measurement points, located in accordance with the standard on a hemispherical measurement surface, with a radius of 1.15 m. The room's acoustic absorption required for calculating the K2 correction factor was determined based on the reverberation time obtained from impulse responses recorded in the room. For this purpose, an omnidirectional sound source was used, consisting of six loudspeakers: BG 20/70W VISATON, assembled in the cubic casting, an amplifier (Bruel & Kjaer 2716-C), a BEHRINGHER ECM 8000 measuring microphone, and an EDIROL UA-5 audio interface, along with a DIRAC 6.0 Bruel & Kjaer system. The MLS signal generated by the DIRAC program was used for the room excitation.

The performance of the acoustical enclosure in terms of IL was determined as the difference of the sound power levels radiated by the unenclosed and enclosed source.

The IL of an acoustic enclosure can be determined more accurately in laboratory conditions in an anechoic room by determining sound power levels using the precision method (PN-EN

ISO 3745, 2012), which was the subject of previous research (Kosała *et al.*, 2020). In the current research, the use of the survey method was aimed at reflecting measurement conditions in which the nature of the sound field is similar to that occurring in industrial conditions, and it seems to be a sufficient approach to validate the results obtained from the calculation model for the IL of sound-insulating enclosures proposed in this article.

An enclosure with a set of five identical walls was tested for different baffle types, with the material data shown in Table 1.

Table 1. Material data of the tested enclosure walls.

	Aluminium	Plexiglass	Steel
Density (r) [kg/m^3]	2800	1190	7850
Thickness (h) [m]	0.002 0.003	0.005 0.015	0.001
Young's modulus (E) [GPa]	70	3.5	207
Poisson's Ratio (ν) [-]	0.35	0.35	0.3
Loss factor (η) [-]	0.01	0.02	0.01

Assuming that the enclosure has perfectly rigid walls, the mode frequencies (eigenfrequencies) $f_{m,n,p}$ of the enclosure cavity can be determined according to the well-known formula (Hopkins, 2007):

$$f_{m,n,p} = \frac{c_0}{2}\sqrt{\left(\frac{m}{L_x}\right)^2 + \left(\frac{n}{L_y}\right)^2 + \left(\frac{p}{L_z}\right)^2} \tag{1}$$

where: c_0 is the speed of sound in the air [m/s], m, n and p are the particular mode numbers, and L_x, L_y, L_z are dimensions of the enclosure cavity [m].

The eigenfrequencies calculated in this way for a simple, rectangular-shaped cavity are an approximation. In reality, the air cavity inside the enclosure is reduced by the presence of a loudspeaker, which has a case with dimensions of 0.24 m × 0.24 m × 0.115 m. Calculations of the eigenfrequencies for such a complex geometry of the air cavity inside the enclosure were possible using a numerical model and simulations performed in COMSOL Multiphysics 6.3.

Table 2 shows the values of the eigenfrequencies, calculated for the enclosure cavity with and without a loudspeaker.

Table 2. Eigenfrequencies of the enclosure cavity with and without a loudspeaker.

Mode	Eigenfrequency [Hz]		
	Enclosure cavity without a loudspeaker		Enclosure cavity with a loudspeaker
	Formula (1)	COMSOL Multiphysics	COMSOL Multiphysics
1	312.1	312.0	297.3
2	312.1	312.0	297.3
3	312.1	312.0	319.5
4	441.4	441.3	427.9
5	441.4	441.3	427.9
6	441.4	441.3	436.1
7	540.6	540.4	534.3
8	624.2	624.1	594.6
9	624.2	624.1	601.2
10	624.2	624.1	643.8

The identical dimensions of the cavity enclosure without a loudspeaker (L_x=L_y=L_z) show that each of the axial modes (#1-3 and #8-10) as well as each of the tangential modes (#4-6) have the same values. For an enclosure cavity reduced by the presence of a loudspeaker, the values of the eigenfrequencies are more varied.

3. Insertion loss calculation model

Previous studies have shown that, when determining the effectiveness of a sound-insulating enclosure, good results in the form of small discrepancies between the calculation and the experimental results can be obtained using the model described in (Kosała, 2022). This model determines the effectiveness of a sound source enclosed with sound-insulating walls of dimensions 0.7 m × 0.7 m. For cube-shaped enclosures, built of sound-insulating walls of dimensions 0.55 m × 0.55 m, a similar approach to that presented in (Kosała, 2022) is proposed, however, it is defined by the relationship:

$$IL = \begin{cases} 10log[cos(kd) - 0.37\rho h\omega sin\ (kd)/\rho_0\, c_0]^2, for f \leq 1.9 f_{0,0,1} \\ 10log\dfrac{\bar{\alpha}_{rand}}{10^{-0.1TL} + e^{-0.31R_w}}, for f > 1.9 f_{0,0,1} \end{cases} \tag{2}$$

where: k is the wavenumber of sound, d is the distance of the top panel of the tested enclosure from the floor, ρ is the material density, h is the material thickness, ω is the angular frequency, ρ_0 is the air density, c_0 is the speed of sound in the air, $f_{0,0,1}$ is the first axial mode frequency of the enclosure cavity, $\bar{\alpha}_{rand}$ is the random incidence sound absorption coefficient of bare enclosure walls (Kosała, 2022; Ver, Beranek, 2006), TL is the sound transmission loss of the enclosure wall, R_w is the weighted sound reduction index of the enclosure wall, and f_c is the coincidence frequency of the enclosure wall (Kosała, 2022; Ver, Beranek, 2006).

A new calculation model is proposed for insertion loss for the relevant frequency ranges depending on the eigenfrequency $f_{0,0,1}$ enclosure cavity. For the low-frequency range, in which $f \leq 1.9f_{0,0,1}$ of the enclosure cavity, a modified Oldham model (Oldham, Hillarby, 1991; Kosała, 2022) for a clamped boundary condition is proposed. For the high-frequency range, where $f > 1.9f_{0,0,1}$ of the enclosure cavity, the proposed model is a function of $\bar{\alpha}_{rand}$, TL and R_w.

The quantity 0.32 in formula (16) (Kosała, 2022) was replaced by 0.37 in formula (2) for the low frequency range. This value was obtained based on the results of new experimental tests of the IL spectral characteristics, carried out for five variants of the wall materials, as given in Table 1. For the range of 100 to 500 Hz of the centre frequencies of the 1/3 octave bands, with the assumed value of 0.37, a relatively low RMSE value of 3.9 dB was obtained, averaged for five variants, with a simultaneously high value of the Pearson correlation coefficient r=0.88, between the results obtained from calculations using the model and from experimental tests. Similarly, new experimental tests were used for the higher frequency range, from 630 Hz to 5 kHz. The assumption of a value of 0.31 for R_w resulted in a relatively small five-variant average of RMSE=2.73 dB, while the obtained Pearson correlation coefficient was high, r=0.85.

4. Results

4.1. Calculation of sound insulation properties of the enclosure walls

To determine the transmission loss of a homogeneous baffle with external dimensions of 0.55 m × 0.55 m, needed to determine the insertion loss of a sound-insulating enclosure using the proposed model (1), the material data of the baffle, shown in Table 1, and the Davy-Sharp model proposed in (Kosała, 2019) were used. Previous studies have shown that such a combination of two models, Davy (Davy, 2009) and (Sharp, 1973), for the relevant frequency ranges, resulted in smaller discrepancies in TL calculations of single homogeneous baffles with dimensions of 1 m × 2 m, in relation to laboratory tests, than when using commercial software and when the models were used separately (Kosała, 2019). The calculation results in the form of TL spectral characteristics in 1/3 octave frequency bands for five materials with thicknesses ranging from 1 to 15 mm are shown in Figure 3.

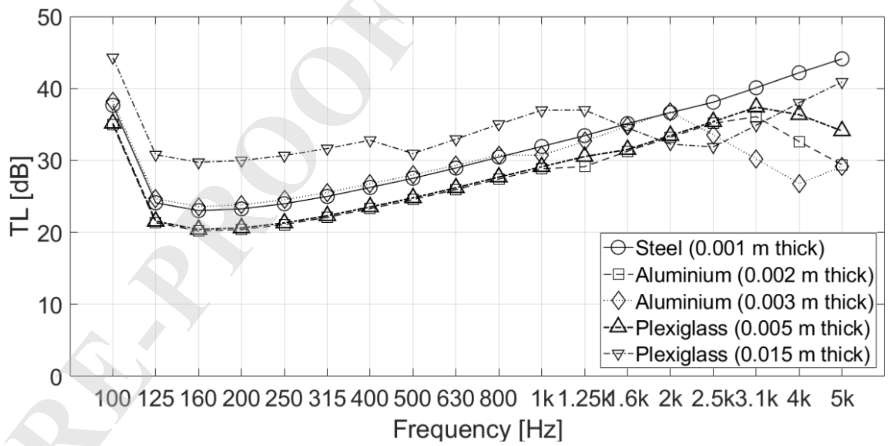


Fig. 3. Transmission loss of the tested enclosure walls obtained using the Davy-Sharp calculation model.

The curves for the aluminium (0.003 m thick) and the plexiglass baffle (0.015 m thick) show a characteristic reduction in sound insulation in the higher frequency range, related to the occurrence of the coincidence phenomena. For the remaining baffles, the coincidence frequency

f_c is above the highest centre frequency of the 1/3 octave bands in the considered range, which is 5 kHz. The calculated f_c values for the tested enclosure walls are shown in Table 3.

Table 3. The weighted sound reduction indices $R_w(C;C_{tr})$ and the coincidence frequencies f_c of the tested enclosure walls.

Enclosure wall material	$R_w(C;C_{tr})$ [dB]	f_c [Hz]
Steel (0.001 m thick)	32(-1;-3)	12042
Aluminium (0.002 m thick)	29(-1;-3)	6072
Aluminium (0.003 m thick)	32(-1;-2)	4048
Plexiglass (0.005 m thick)	29(0;-2)	6843
Plexiglass (0.015 m thick)	34(0;0)	2281

In the low frequency bands (Fig. 3), where the radiation efficiency of a finite-sized baffle is reduced, a specific increase in sound insulation can be observed. Based on the TL spectral characteristics, the weighted sound reduction index R_w was calculated for each type of enclosure wall tested. The values of this index, as well as the spectral adaptation indices C and C_{tr}, for the tested enclosure walls, are shown in Table 3. Comparing the R_w values (Table 3) for enclosure walls of dimensions 0.55 m × 0.55 m, made of steel (0.001 m thick) and aluminium (0.002 m thick) with the values of this parameter for baffles of dimensions 0.7 m × 0.7 m [14], it can be seen that smaller baffles have 1 dB higher R_w values than larger baffles. This is influenced by the TL spectral characteristics, which in the low frequency bands have slightly higher values for smaller baffles compared to larger ones. This also applies to baffles of larger dimensions (1 m × 2 m), for which the steel baffle (0.001 m thick) has R_w=30 dB, and the aluminium baffle (0.002 m thick) has R_w=27 dB (Kosała, 2019).

4.2. Calculation of insertion loss for the enclosure using the proposed model

The calculation results using the proposed insertion loss model (2) for the five tested variants of sound-insulating enclosures are shown in Figure 4.

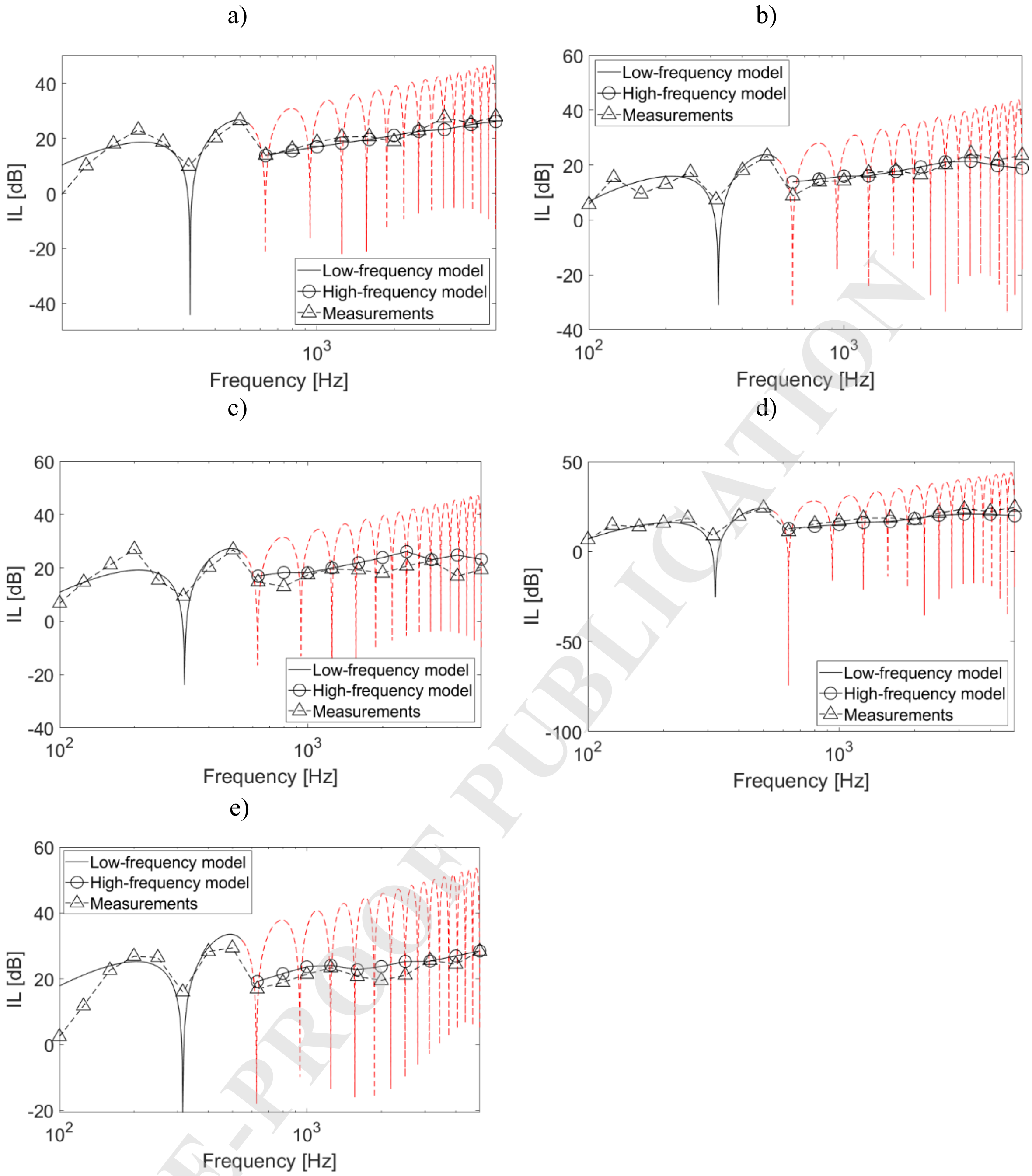


Fig. 4. Insertion loss (IL) of enclosures with walls of materials: a) steel (1 mm thick) b) aluminium (2 mm thick), c) aluminium (3 mm thick), d) plexiglass (5 mm thick), e) plexiglass (15 mm thick), obtained using the low-frequency model, high-frequency model and measurements.

After recalculating the IL values for the 1/3 octave bands for the low frequency range, it was possible to compare the results of calculations and experimental tests using the Pearson correlation coefficient (*r*) and Root Mean Square Error (RMSE). Close agreement of the results was obtained, both in the lower and higher frequency ranges, as shown in Table 4. The Pearson correlation coefficients between the results of calculations and experimental tests are high ($r \geq 0.8$), for all types of enclosure walls for the lower frequency range (centre frequencies of 1/3 octave bands, lower than 600 Hz). For the frequency range higher than 600 Hz, the values of $r \geq 0.86$, except for the 3 mm thick aluminium baffle, for which $r = 0.61$. Considering the full frequency range, the Pearson coefficient is high ($r \geq 0.73$).

Table 4. Pearson correlation coefficients and Root Mean Square Errors for predicted IL in comparison with experimental tests for the five enclosure wall materials.

Enclosure wall material			Steel	Aluminium	Aluminium	Plexiglass	Plexiglass
Thickness (h) [m]			0.001	0.002	0.003	0.005	0.015
r	Frequency range	low	0.88	0.87	0.85	0.95	0.80
		high	0.94	0.86	0.61	0.92	0.91
		full	0.9	0.87	0.73	0.94	0.81
RMSE [dB]	Frequency range	low	4.5	2.8	3.7	2.0	6.6
		high	1.9	2.7	4.2	2.3	2.5
		full	3.3	2.7	4.0	2.2	4.8

The RMSE values for the low frequency range are from 2 dB (0.005 m thick plexiglass baffle) to 6.6 dB (0.015 m thick plexiglass wall). For the higher frequency range, the RMSE ranges from 1.9 dB (0.001 m thick steel baffle) to 4.2 dB (0.003 m thick aluminium baffle). Over the entire frequency range, the RMSE is between 2.2 and 4.8 dB.

Figure 4 shows the red dashed line indicating the further course of IL, after applying the modified Oldham formula (line 1 of formula (2)), but for $f > 1.9 f_{0,0,1}$. The nulls on the graphs correspond to the axial resonant frequencies of the enclosure cavity $f_{0,0,1}$, $f_{0,0,2}$, etc. Table 5 shows the eigenfrequencies of the enclosure cavity determined by this method and calculated using formula (1).

Table 5. Eigenfrequencies of the enclosure cavity calculated from formulas (1) and (2).

				Eigenfrequency [Hz] $f_{m,n,p}$	
The axial mode number	m	n	p	Formula (1)	Modified Oldham model (Formula (2))
1	0	0	1	312	319
2	0	0	2	624	628
3	0	0	3	936	939

4	0	0	4	1248	1250
5	0	0	5	1560	1562
6	0	0	6	1873	1874
7	0	0	7	2185	2186
8	0	0	8	2497	2498
9	0	0	9	2809	2810
10	0	0	10	3121	3122
11	0	0	11	3433	3434
12	0	0	12	3745	3746
13	0	0	13	4057	4058
14	0	0	14	4369	4370
15	0	0	15	4681	4682

The eigenfrequency values of the enclosure cavity obtained by the two methods differ slightly, as shown in Figure 5. The greatest differences are for the (0,0,1) mode, however, they decrease with increasing frequency.

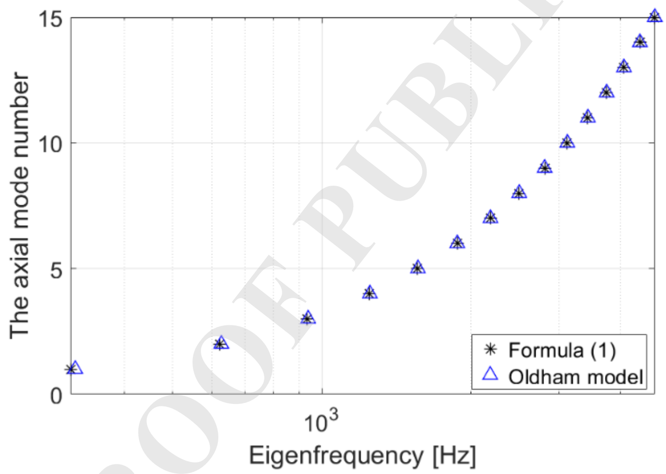


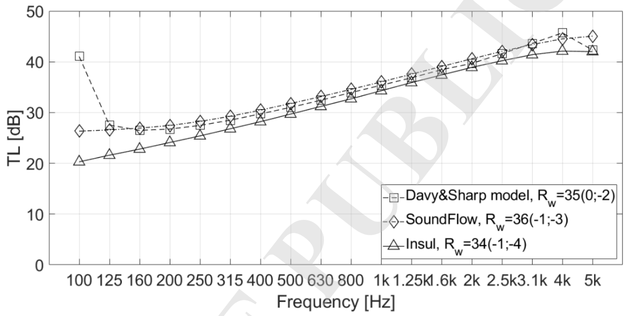
Figure. 5. Graph of the dependence of eigenfrequencies of the enclosure cavity between the values obtained from formulas (1) and (2).

It should be taken into account that the calculations using formula (1) are approximate, because the walls of the tested enclosure cannot be perfectly stiff when excited by a sound source.

5. Model validation and the influence of the wall's TL on the enclosure's IL

The proposed model of enclosure sound insulation effectiveness was tested in preliminary studies for five variants, each comprising five identical walls made of different materials. Based on the material data and the calculation of the enclosure wall's TL using the Davy-Sharp model, the IL of these enclosures was determined. In the next stage of the study, the model was validated, taking into account four further sets of five walls made of the following materials: 1.5 and 2 mm thick steel, 10 mm thick plexiglass, and 1 mm thick aluminium. This time, how other models, such as SoundFlow (AFMG SoundFlow, 2011) and Insul (INSUL, 2017), affect the final result of the enclosure IL calculations was examined. First, the TL spectral characteristics were determined and the R_w indices were calculated based on them, as shown in Fig. 6.

a)



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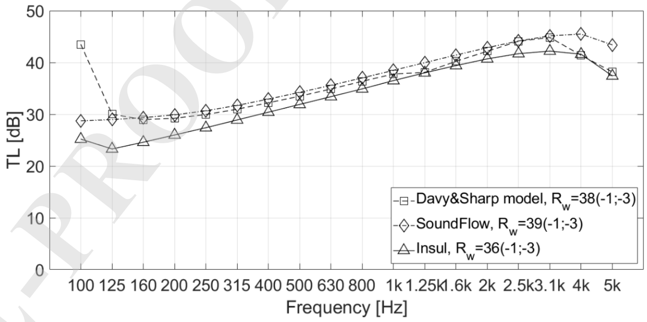

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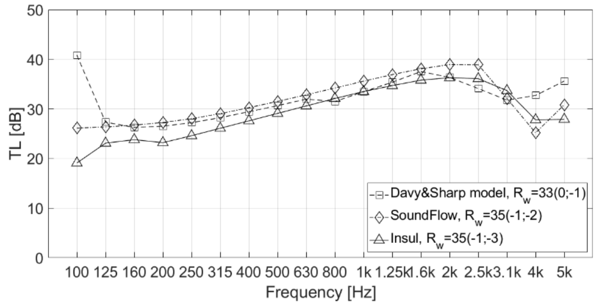

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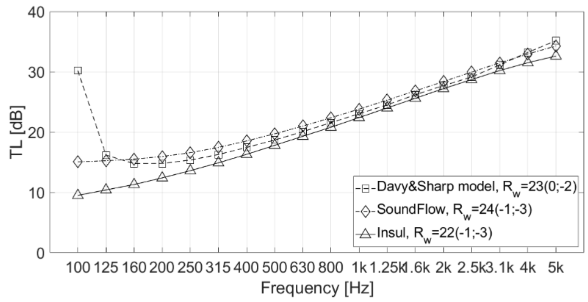
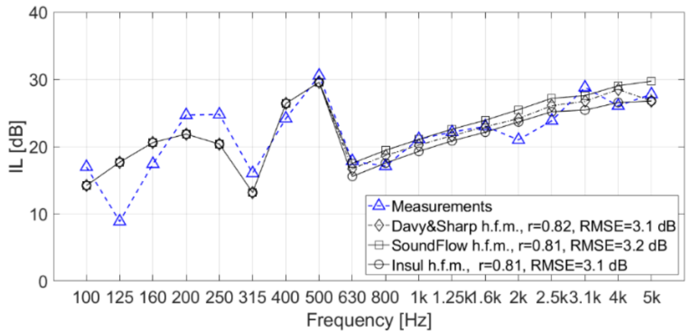


Fig. 6. Transmission loss calculated from the Davy&Sharp model, AFMG SoundFlow and Insul for enclosure walls made of: a) steel 0.0015 m thick, b) steel 0.002 m thick, c) plexiglass 0.01 m thick and d) aluminium 0.001 m thick.

For calculations in the AFMG SoundFlow and Insul programs, the dimensions of the baffles were assumed to be 0.6 m × 0.6 m, because it was not possible to take into account the dimensions of the actual walls of 0.55 m × 0.55 m. Figure 6 shows discrepancies in the TL calculations, especially in the lower frequency bands. It should be noted that, although the IL calculations take into account the TL of the wall from the centre frequency of the 1/3 octave band equal to 630 Hz, and in the higher frequency range the discrepancies are relatively small, R_w, on which IL also depends, is calculated for the 1/3 octave bands from 100 Hz to 3.1 kHz. The discrepancies between the calculated R_w values range from 2 to 3 dB. In the higher frequency bands for a 10 mm thick plexiglass baffle, a noticeable reduction in sound insulation due to coincidence is observed. Due to the results being presented in 1/3 octave frequency bands, the coincidence frequency value, f_c=3421 Hz, cannot be precisely determined in the graphs. For the AFMG SoundFlow and Insul models, f_c=4 kHz, and for the Davy-Sharp model, f_c=3.1 kHz.

The results of the enclosure IL calculations for the four tested new wall material sets, including the higher frequency ranges of the three models for which TL was calculated, are shown in Fig. 7.

a)



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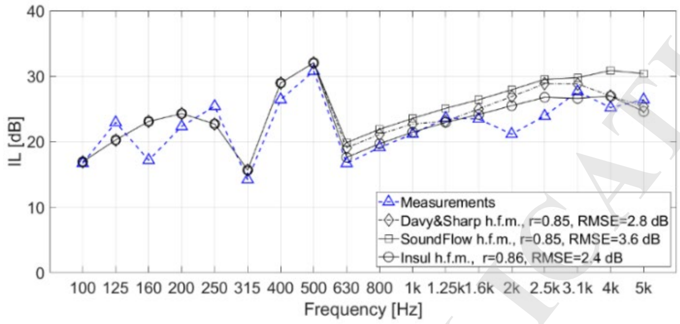

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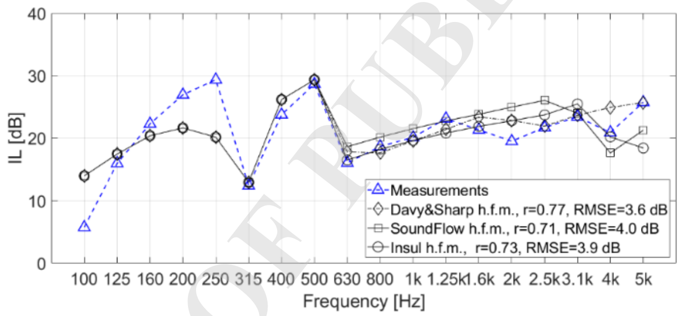

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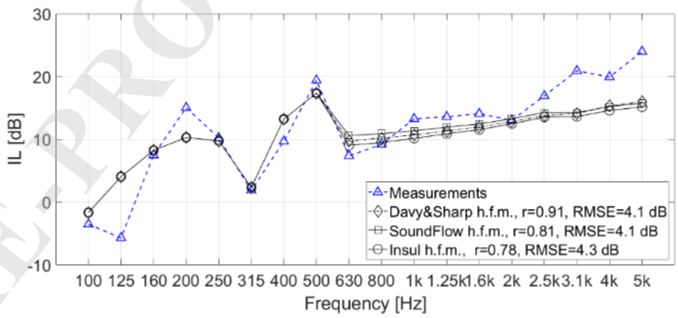

Fig. 7. Insertion loss calculated from the proposed calculation model: modified Oldham for the low-frequency range and Davy&Sharp model, AFMG SoundFlow and Insul for the high-frequency range, for enclosure walls made of: a) steel 0.0015 m thick, b) steel 0.002 m thick, c) plexiglass 0.01 m thick and d) aluminium 0.001 m thick.

The smallest RMSE discrepancies occurred for the 2 mm thick steel baffle ($RMSE_{avr}$=2.9 dB), and the largest for the 1 mm thick aluminium baffle ($RMSE_{avr}$=4.2 dB). The averaged Pearson correlation coefficients r for all four baffles calculated using the individual models are:

0.84 for Davy-Sharp, 0.8 for AFMG SoundFlow, and 0.8 for Insul. The averaged RMSE values are: 3.40 dB for Davy-Sharp, 3.73 dB for AFMG SoundFlow, and 3.43 dB for Insul. This indicates that the Davy-Sharp model showed both the highest correlation of IL characteristics with the experimental results among the three tested models and the lowest averaged RMSE.

6. Effectiveness of sound-insulating enclosures of different sizes made from the same wall materials

Experimental tests and modelling studies of the effectiveness of small enclosures (wall dimensions of 0.55 m × 0.55 m) described in the article and large enclosures (wall dimensions of 0.7 m × 0.7 m) described in (Kosała, 2022), carried out on sets of identical wall materials, such as steel 0.001 m thick, aluminium 0.002 m thick, and plexiglass 0.005 m and 0.015 m thick, enabled a comparison of their sound insulation properties. Figure 8 shows the results of experimental tests, and Figure 9 shows the results of modelling studies.

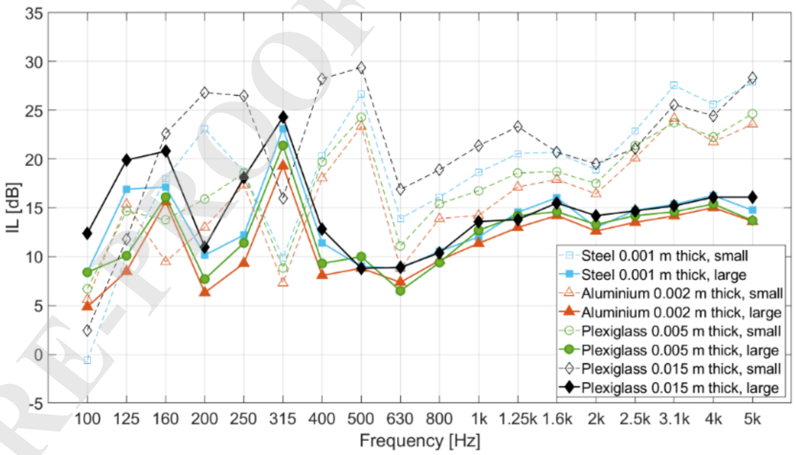

Fig. 8. Insertion loss obtained from experimental tests of small and large enclosures made of wall materials: steel (0.001 m thick), aluminium (0.002 m thick), and plexiglass (0.005 and 0.015 m thick).

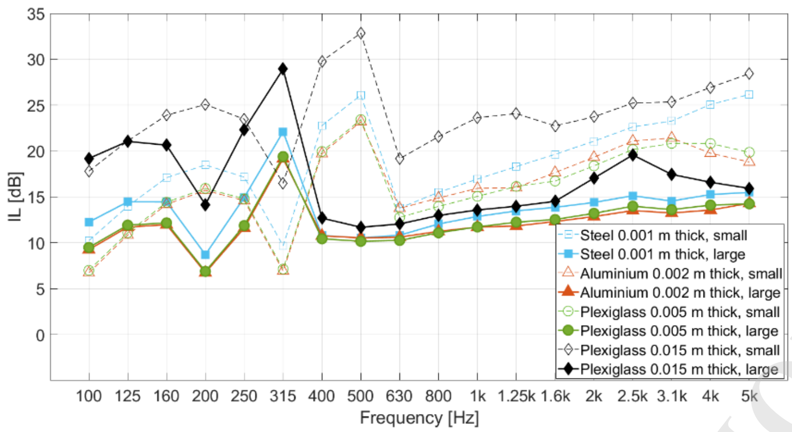

Fig. 9. Insertion loss obtained using calculation models for the IL of small and large enclosures made of wall materials: steel (0.001 m thick), aluminium (0.002 m thick), and plexiglass (0.005 and 0.015 m thick).

The IL spectral characteristics (Fig. 8) show that IL is higher for smaller enclosures, especially in the mid- and high-frequency bands. For smaller enclosures in these ranges, greater variation in IL results (5-10 dB) can be observed for the tested materials than for larger enclosures (approximately 3-5 dB). For larger enclosures, the influence of the eigenfrequencies of the enclosure cavity on the IL spectral characteristic is observed up to 315 Hz, corresponding to 1.5f_c of the enclosure wall, while for smaller enclosures it is more dominant, up to 500 Hz, corresponding to 1.9f_c of the enclosure wall. The most effective among the tested baffles is the 15 mm thick plexiglass one, however, for smaller enclosures, the influence of coincidence, which is evident in the TL spectral characteristic of such walls, is more noticeable on the IL curves, while for larger enclosures, the IL characteristic in the 2 kHz region is flatter (f_c=2281 Hz). The IL curves for the calculation models (Fig. 9) are very similar to the corresponding curves obtained from the experimental tests, as shown in Figure 8.

Table 6 summarizes the Pearson correlation coefficients and RMSE for the IL calculation models with respect to the experimental tests for enclosures with wall dimensions of 0.55 m × 0.55 m and 0.7 m × 0.7 m.

Table 6. Pearson correlation coefficients and Root Mean Square Errors for predicted IL in comparison to experimental tests for the same enclosure wall materials and enclosure wall dimensions of 0.7 m × 0.7 m and 0.55 m × 0.55 m.

Enclosure wall material	Thickness, h, [m]	Enclosure wall dimensions, [m]			
		0.7 × 0.7		0.55 × 0.55	
		r	RMSE, [dB]	r	RMSE, [dB]
Steel	0.001	0.87	1.80	0.90	3.33
Aluminium	0.002	0.86	2.12	0.87	2.74
Plexiglass	0.005	0.89	1.75	0.94	2.17
Plexiglass	0.015	0.87	2.98	0.81	4.80
	average	*0.87*	*2.16*	*0.88*	*3.26*

Two models for smaller and larger enclosures, proposed in (Kosała, 2022), showed a high correlation coefficient of the IL spectral characteristics calculated and related to the characteristics obtained from experimental tests. The average values of these coefficients are 0.9. The IL estimation using the calculation model showed approximately 1 dB lower average RMSE values for larger enclosures compared to smaller ones. In both cases, the average RMSE values are not high and range from about 2 to 3 dB, except for the small enclosure made of 15 mm plexiglass, where the prediction error is close to 5 dB.

7. Conclusions

As a result of experimental tests aimed at determining the effectiveness of an enclosed sound source imitating a noisy machine or device, IL characteristics were determined, first for five different wall material variants, and in the second stage of the study, for a further four variants. A total of nine wall material variants were tested: steel with thicknesses of 1, 1.5, and 2 mm, aluminium with thicknesses of 1, 2, and 3 mm, and plexiglass with thicknesses of 5, 10, and 15 mm. The determined IL curves are very similar, and it can be roughly concluded that for the medium and high frequency ranges, they are shifted towards higher IL values, corresponding to the single-number weighted sound insulation index R_w of the given wall. The worst performance was shown by enclosures made of 1 mm thick aluminium walls (R_w=22 dB), while the best performance was achieved by enclosures made of 2 mm thick steel walls (R_w=38 dB).

The IL curves up to a certain centre frequency of the 1/3 octave bands, equal to 500 Hz, i.e., for $f \leq 1.9 f_{0,0,1}$, have characteristic curves, corresponding to the enclosure air cavity resonances. Above this frequency, the IL values are less differentiated for subsequent centre frequencies.

The proposed calculation model for the IL of sound-insulating enclosures was developed based on experimental tests conducted in the first stage, covering five variants of material walls. In the subsequent stage, the model was validated using four additional variants, taking into account the influence of the calculation model for the wall's TL on the final IL result. The studies showed that the model proposed in earlier studies, a combination of the Davy and Sharp models, yielded better results compared to the models implemented in SoundFlow and Insul software. The Davy-Sharp model showed both the highest correlation of IL characteristics with the experimental results of the three models tested and the lowest averaged RMSE. However, it should be taken into account that only the Davy-Sharp model could take into account the actual dimensions of the enclosure wall of 0.55 m × 0.55 m. Limitations in entering input data into computer programs allowed calculations to be made for walls with dimensions of 0.6 m × 0.6 m, i.e., only close to the actual ones, which could also have had a certain impact on the accuracy of calculations using these models. A comparison of the effectiveness of enclosures made of the same materials, with walls measuring 0.55 m × 0.55 m, was made with enclosures analysed in previous studies, with walls measuring 0.7 m × 0.7 m. Based on a comparison of the IL spectral characteristics, it was found that the IL is higher for the smaller enclosures, especially in the mid- and high-frequency bands. Based on IL calculations using models, the averaged RMSE values were approximately 1 dB lower for the larger enclosures compared to the smaller ones. In both cases, the averaged RMSE values were not high, ranging from about 2 to 3 dB, except for the small enclosure made of 15 mm plexiglass, where the prediction error was close to 5 dB. Both the models for smaller enclosures and for larger ones, proposed in (Kosała, 2022), showed a high correlation coefficient of the IL spectral characteristics calculated and related to the characteristics obtained from experimental tests, amounting to r=0.9. The proposed calculation models can be helpful in cost-free estimation of the acoustic efficiency of a solution in the form of a cube-shaped sound-insulating enclosure with the wall dimensions that were the subject of the study, assuming the appropriate material data needed for these calculations is available.

Testing the acoustic efficiency of sound-insulating enclosures is a significant challenge, and although it requires a different approach to calculating their effectiveness compared to sound-absorbing and insulating enclosures, where the impact of resonances within the enclosure, which sometimes counteracts their effectiveness, is mitigated by sound-absorbing material installed on the side of the sound source, it also has many practical applications. These are particularly relevant in cases where smooth, sound-reflecting transparent walls, such as plastic or glass, make it possible to monitor the operating, enclosure device. Another area of application involves situations where, due to the risk of bacterial growth in porous and fibrous materials, sound-absorbing and insulating enclosures are inappropriate.

The obtained research results may have practical applications in the selection of walls of cube-shaped sound-insulating enclosures.

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Conflict of interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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