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Insertion loss of enclosures with lined slits

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Summary
An air slit with one of the boundaries created by an absorbing lining is an acoustic system that can introduce the transmission loss (TL) of high values, especially in the high frequency range. The aim of this paper is evaluation of overall insertion loss (IL) in acoustic enclosures caused by air slits. For this purpose, two MDF sound insulating enclosures with different sizes were constructed. Enclosures were elevated in order to create slits with adjustable height. Because enclosures were acoustically adapted, an absorbing boundary was naturally created. Mechel's model was utilized to predict TL of that kind of absorbing slits. The insertion losses of both enclosures were measured according to ISO 11546-1. Next, simulation of insertion loss has been performed (two models have been used: a well-known simple formula and a SEA model). It was noticed, that difference between results obtained with using simple formula and with SEA model is negligible, because a transmission across slits (modelled in SEA as an non-resonant transmission) is much higher than a transmission across enclosure walls in a wide frequency range. Results of simulations and measurements have been compared. A good agreement occurs in a case of narrow slits. Furthermore, results confirmed the importance of providing high modal overlap conditions while using statistical models in acoustic simulation.

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1. Introduction

Sound insulating enclosures often comprise openings and slits. Leaks introduced through the slits can significantly reduce the sound insulation properties of the enclosures. However, for technological reasons, the presence of holes is often unavoidable. In this situation, acoustic silencers are used to limit the transmission of sound through openings. In the case of openings without silencers, it is often assumed that their transmission loss is equal to 0 dB, which allows their simple inclusion in acoustic models. There are also more precise models that allow to more accurately determine the transmission loss of such openings [9]. As part of this work, the impact of damped slits on insertion loss of enclosure was examined. The top wall of the considered slits was also a fragment of mineral wool placed inside the casing. The Mechel model was used to estimate the insulation properties of such leaks. The Mechel's model is a good approximation of the actual transmission loss if the considered slits are narrow, that is, they satisfy the condition $k_0 a \ll 1$, where k_0 is a wavenumber and a is the height of the slits. In order to validate this condition, slits differing in height and introducing the following leak ratios were applied: 1%, 2% and 5%. The obtained transmission coefficients have been introduced to SEA model of the enclosure in order to predict insertion loss.
The basic requirement of SEA models is to ensure a large modal overlap in subsystems. In order to check the effect of modal overlap on the accuracy of statistical models, two enclosures of different sizes were built. A larger enclosure showing a higher density of natural vibrations in individual frequency bands should be more suitable for statistical models.
An additional aspect of the research was the comparison of two measuring methods of insertion loss presented in the ISO 11546-1 standard: real source method (AS) and reciprocity method (RM). The AS method is derived directly from the definition of insertion loss and takes into account the influence of the sound source geometry on the IL characteristics. For this reason, it is recommended in the first instance by the standard. The reciprocity method uses the fact that changing the receiver's place and the acoustic source should not affect the measurement result. Therefore, in the RM, the microphone is placed inside the enclosure instead of the source.

2. Theory

2.1. Transmission loss of lined slits

In order to determine the transmission coefficient of the lined slit, the characteristic impedance of the mineral wool Z_y forming the slit should be evaluated. The characteristic impedance can be estimated by knowing the flow resistance of the material under test (for example one can use the Delany and Bazley model or Bies and Hansen model [1]). The Bies and Hansen model was used in this research. The transmission coefficient was determined by the matrix method, which as the input data takes the depth and the height of the slit, as well as the propagation constant Γ_a and the characteristic impedance Z_a of the medium inside the slit [10]. In the case under consideration, for Γ_a and Z_a one should not accept parameters suitable for air (because the upper layer of the gap introduces damping). Also, the parameters associated directly with the damping material will not be adequate, because the material does not fill the gap. In order to find Γ_a and Z_a, the characteristic equation for locally reacting lining needs to be solved, with respect to ϵa [7]:

$$\epsilon a \cdot \tan \epsilon a = jU \quad (1)$$

where a is the slit height, j is and imaginary unit, $\epsilon^2 = {\Gamma_a}^2 + {k_0}^2$, $U = k_0 a Z_0 G_y$, k_0 is the wavenumber in air, Z_0 is characteristic impedance of air and $G_y = \frac{1}{Z_y}$. Roots of equation 1 can be found numerically. If the $k_0 a << 1$ condition is fulfilled, the following low-frequency approximation may be used to find the solution for least attenuated mode:

$$(\epsilon a)^2 = \frac{105 + 45jU \pm C}{20 + 2jU} \quad (2)$$

$$C = \sqrt{11025 + 5250jU - 1605U^2}$$

The sign of C in the equation 2 is chosen so as to obtain the minimum value of expression:

$$\Gamma_a a = \sqrt{(\epsilon a)^2 - (k_0 a)^2} \quad (3)$$

Then the propagation constant can be derived directly from 3, whereas the characteristic impedance is determined from:

$$\frac{Z_a}{Z_0} = \frac{jk_0}{\Gamma_a} \quad (4)$$

2.2. SEA model of the enclosure

The insertion loss of enclosure is defined by the logarithm of a ratio of the acoustic power radiated by the noise source without the enclosure to the power radiated by the enclosure containing the source [3]. One of the methods to predict IL of enclosures that have proven their effectiveness is Statistical Energy Analysis. In order to create the SEA model of the enclosure, the method presented by Lei, Jie and Sheng [5] was used. The SEA model consisted of 11 subsystems: the acoustic field inside the enclosure, 5 fields of free bending waves in panels and 5 fields of forced bending waves in panels. Thus, each panel forming the enclosure has been described with two SEA subsystems. The model includes the flow of vibratory energy between the panels in the resonance path and the transmission of acoustic energy through the gaps (forced transmission introduced by indirect coupling).

To determine the acoustic power radiated by the enclosure, the mean square velocities of forced (v_f) and free (v_r) waves appearing on the panels (obtained from the SEA model) and the radiation efficiency of panels were used. The radiation efficiency of forced bending waves field σ_f was determined using Davy's formula [2] and the radiation efficiency of free bending waves field σ_r was determined from the relationships given by Lyon [6]. Formulas for σ_f and σ_r have a more complex character, so interested readers are referred to the source articles.

Finally, the power radiated by the enclosure for each frequency band considered was determined from the dependence:

$$P_e = \sum_{i=1}^{5} \rho_0 c_0 S_i \sigma_{r,i} {v_{r,i}}^2 + \sum_{i=1}^{5} \rho_0 c_0 S_i \sigma_{f,i} {v_{f,i}}^2 \quad (5)$$

For comparison purposes, a simple model defined by the following relationship was also used:

$$IL = \overline{R} + 10 \log \overline{\alpha} \quad (6)$$

$\overline{R}$ and $\overline{\alpha}$ were computed as area-weighted average values. $\overline{R}$ is a function of transmission coefficient of enclosure panel τ, area of the enclosure panel S, transmission coefficient of the slit τ_s and area of the slit S_s:

$$\overline{R} = 10 \log \left(\frac{S + S_s}{S\tau + S_s \tau_s} \right) \quad (7)$$

$\overline{\alpha}$ consists of absorption coefficient introduced by rockwool α, area of the enclosure panel S, absorption coefficient of the the slit α_s and area of the slit S_s:

$$\overline{\alpha} = \frac{S\alpha + S_s \alpha_s}{S + S_s} \quad (8)$$

3. Measurements

The basic objects of the study were two rectangular enclosures made of MDF: enclosure E1 and enclosure E2. Enclosure E2 was twice as large as the E1. External dimensions and volumes of enclosures' interiors are shown in the table I. The thickness of MDF boards was 18 mm. The enclosures were lined

Table I. Dimensions of enclosures

enclosure	$E1$	$E2$
length [m]	0,96	1,20
width [m]	0,80	1,00
height [m]	0,64	0,80
volume [m^3]	0,44	0,88

Table II. Mechanical parameters of MDF panels

parameter	value
density [$\frac{kg}{m^3}$]	760
loss factor [−]	0,01
Young modulus [Pa]	$2,3 \cdot 10^9$
Poissons number [−]	0,3

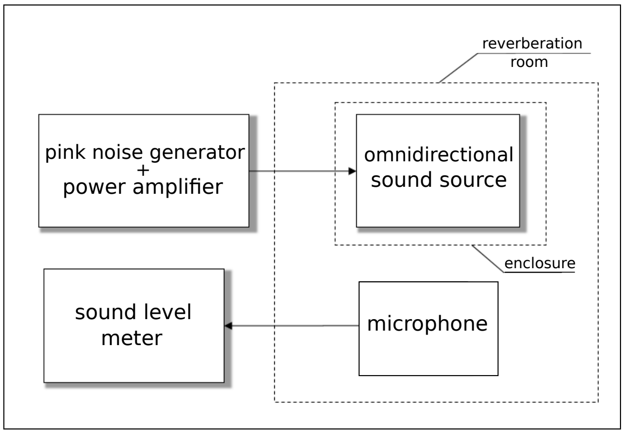

Figure 1. Actual source (AS) measurement method

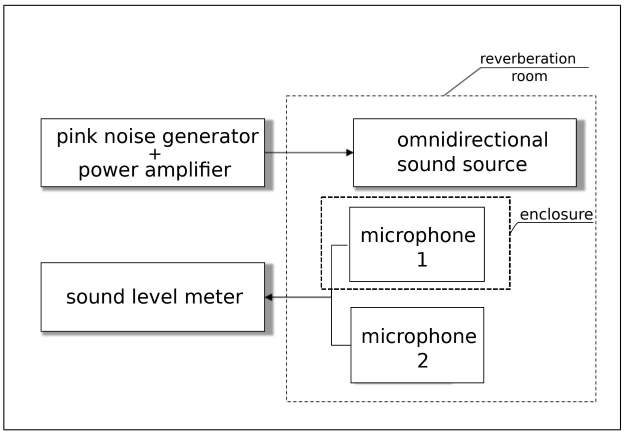

Figure 2. Reciprocity (RM) measurement method

with 50 mm thick mineral wools with various densities. The following mineral wools were used: Rocksonic (40 kg/m^3) and Isover PT80 (80 kg/m^3). The table II presents the mechanical parameters of MDF boards, which were taken for simulation purposes. In order to determine the Insertion loss, measurements were made in a reverberation room in accordance with ISO 11546-1. Two methods were used: the real source method (AS) and the reciprocity method (RM). The diagram of the AS and RM measuring system is shown in figures 1 and 2. A small hole was made in each housing in order to conduct the omnidirectional source wiring. During the measurements, the hole was filled with mineral wool. The measurements of the sound pressure level were carried out at 6 measuring points selected in accordance with the recommendations of ISO 3741. The measurements were carried out in 1/3-octave bands for central frequencies from 100 Hz to 5 kHz. The reverberation room used had a volume of 70 m^3, which allowed to measure the sound pressure above 200 Hz. Therefore, the reverberation chamber had to be qualified according to Annex C of ISO 3741 in order to perform measurements below 200 Hz. For the selected measurement points, the requirements regarding the unevenness of the sound field for all the bands tested were met. Therefore, the obtained results can be considered reliable over the entire range of the frequencies tested. In order to introduce controlled leaks small beams were constructed, which were placed in four corners of the enclosures. It allowed to raise the tested enclosure to the desired height. Because the enclosures were devoid of the bottom, a gap was created with a properly selected surface area. The measurements were carried out for the following leak ratios: 1%, 2% and 5%. The slit heights corresponding to this leak ratios were as follows: 11 mm, 22 mm, 57 mm. The additional measurements were also conducted: TL of the MDF panels, the mineral wool absorption coefficient and the mineral wool flow resistance. The obtained results were used as input data for the IL models.

4. Results and discussion

4.1. Comparison of the SEA model and the simple formula results

Insertion loss measured and simulated by different methods is presented in figure 3. The graph concerns the E1 enclosure with light mineral wool, RM measurement. The trends visible in the figure have also been observed for the remaining measurement variants. In addition to the SEA method and simple formula (6), the figure 3 also include the results for the simplified SEA model consisting of 3 subsystems (where all panels were modeled as one subsystem without division into forced and free fields, while the forced transmission through the panel was implemented via indirect coupling) and for Bies and Hansen models [1] (theoretical and empirical). The applied SEA model predicted the insertion loss by an average of 1 dB higher in relation to the simple dependence and a simplified SEA model. This slightly improved the accuracy of the simulation. It may be related to a different way of taking into consideration non-resonant transmission, which in the Renji's method predicts a slightly lower transmission through the panels [8], which results in a greater IL. Still, the

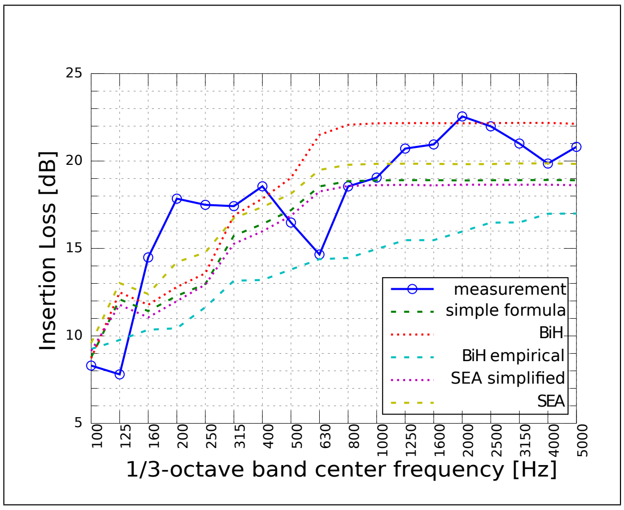

Figure 3. Insertion loss of enclosures obtained by using different models

results obtained are very similar to each other. Because the application of the SEA model in the cases under consideration did not significantly improve the quality of the simulation, in the following points only a model using a simple formula will be used, so as not to obscure the plots.

4.2. The influence of the slit height and the mineral wool density

IL simulations were carried out with taking the gap TL equal to 0 dB in the first place. Mineral wool with a density of $40\frac{\mathrm{kg}}{\mathrm{m}^3}$ and $80\frac{\mathrm{kg}}{\mathrm{m}^3}$ was used, with light wool being cut 4 cm above the edge of the panels. A comparison of the results of these simulations and measurements is shown in figure 4. As expected, the increase in the gap height can be directly related to the decrease in enclosure IL.

The use of denser mineral wool had an impact on increasing the TL of panels, which was observed in direct measurements of TL of panels. However, the discrepancy between the measurement and the simulation shown in 4b for high frequencies is not caused by the increase in the TL of the panels, but by the increase in the TL of the gap itself as a result of the creation of the absorbing layer above the gap. In the high frequency range, the effect of panel TL on enclosure IL is negligible in the case of significant leaks (due to the dominant sound transmission through openings), which makes it possible to compare variants using different wool densities. This is confirmed by the curves plotted on the basis of simulations that reach the same limit value in figures 4a and 4b. In the case of the variant with light wool (figure 4a), a better convergence of simulations and measurements was observed. It can be assumed that mineral wool cut 4 cm above the edge of the panel meant that the approximation of the TL of the gap with the value of 0 dB is more justified. In this case, the measurements did not show such a sharp increase in the IL at high frequencies. This can be an important clue when constructing structures of a similar type. Namely, the layer of mineral wool should go to the very edge of the panel. In turn, for low frequencies the influence of wool density is noticeable, because for low frequencies TL of leakage and TL of panels are comparable. Enclosure E2 with denser wool showed a greater IL compared to the variant with light wool for frequencies below 630 Hz.

Then, the Mechel's model was used to more accurately determine the transmission loss of the gaps, taking into account the sound absorbing lining. A comparison of the results of these simulations and measurements is shown in figure 5. Compared to previous simulations, in this case the simulated IL does not remain constant above 630 Hz. The Mechel's model correctly predicted a non-zero and increasing along with the frequency TL of slits. However, it can also be observed that the Mechel's model achieved the highest precision for the narrowest slit. In turn, the quality of Mechel's prediction decreases as the height of gaps increases. This is in line with the formal condition $k_0 a \ll 1$ set for the considered gap.

4.3. The influence of the enclosure volume

The basic requirement for physical objects modeled using the SEA method is the high density of natural vibrations in the considered frequency bands. Therefore, the larger enclosure is more suitable for statistical methods because the modal density is proportional to the volume of the acoustic resonator. The modal overlap in large enclosures is much higher and makes the values averaged over time and space more representative for the whole system. To study the effect of the modal overlap, IL of two enclosures was measured: E1 and E2. The E1 enclosure has a volume of 0.44 cubic meters, while the E2 enclosure has a volume of 0.88 cubic meters. The results of the measurements are shown in the figure 6. As can be seen, the curve obtained from measurements of the E1 enclosure fluctuates around the values obtained from the model, however, the error made in individual bands is larger in relation to the curve obtained from measurements of the E2 enclosure.

4.4. The influence of the measurement method

Insertion loss measured by RM and AS methods is shown in the figure 7. The presence of the sound source inside the enclosure (machine, omnidirectional source) can affect the IL, especially in the case when the volume of the source is not negligible in relation to the volume of the casing. Mass-spring-mass resonances can arise, where the walls of the enclosure and the machine are mass, while the air inside the enclosure introduces stiffness. In addition, the power radiated by the source loaded with high mechanical impedance (caused by stiffness of air) may be different

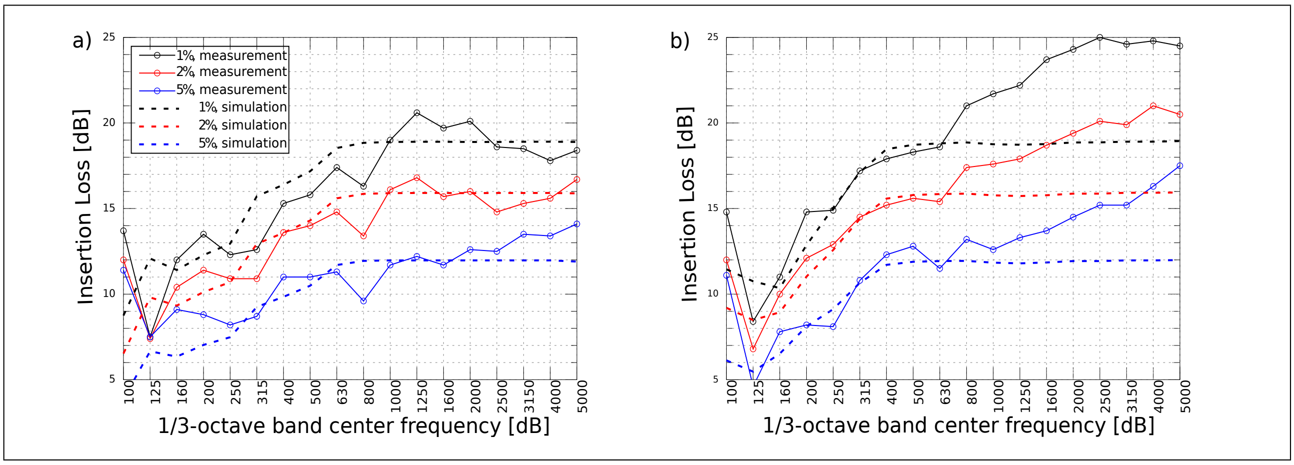

Figure 4. Insertion loss of enclosure for different heights of slits. a) - enclosure with light mineral woll, the wool was cut 4 cm above the edge of the panel; b) - enclosure with dense mineral wool, the wool reached the edge of the panels. The graphs concern the E2 enclosure measured by the RM method.

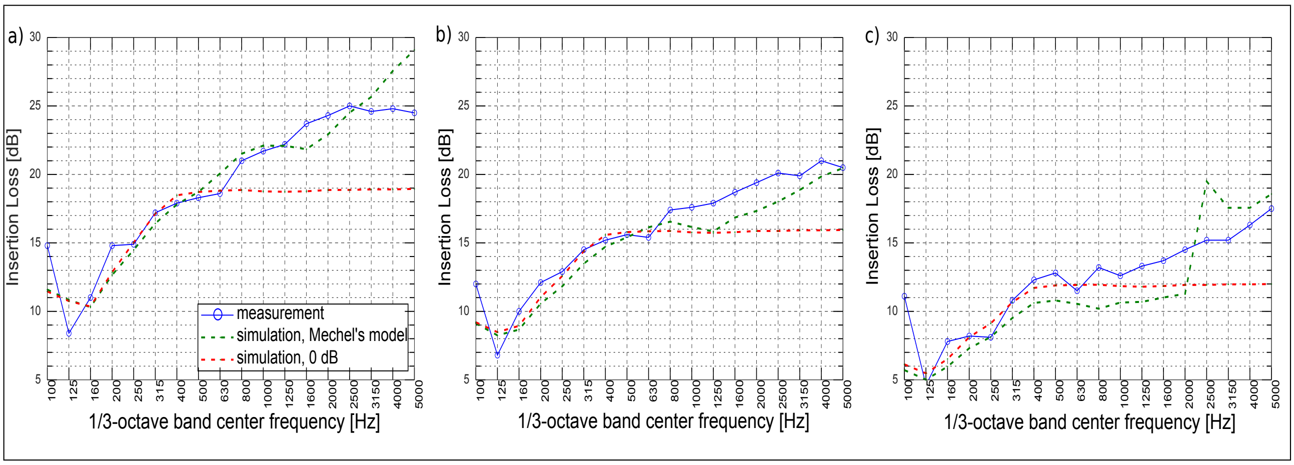

Figure 5. Insertion loss of enclosure for different heights of slits; a) 1% leak ratio; b) 2% leak ratio; c) 5% leak ratio. The slit transmission loss was determined using the Mechels model. The graphs concern the E2 enclosure with dense mineral wool measured by the RM method.

from the power radiated under low load conditions (in case the enclosure is removed). This can be the reason for obtaining higher IL values in the case of AS measurements. Such phenomena are not included in statistical methods, which results in a worse convergence between the results obtained by the AS method and the results obtained from simulations. The convergence of measurements and simulations is improved when using the RM method. The presence of the measuring microphone disturbs the acoustic field inside the enclosure to a much lesser degree, which allows for better prediction with the help of models. However, it should be remembered that the RM method is intended only for general purpose enclosures, while IL of enclosures dedicated for a specific noise source should be determined using the AS method [4]. The research results, however, indicate that the RM method allows to obtain lower IL values, which is a safer option when designing the enclosures in order to reduce the noise level to acceptable values.

5. CONCLUSIONS

The work showed that the differences between the SEA model and simple expression for insertion loss are blurred when analyzing enclosures with significant leaks. The numerous additional transmission paths included in the SEA model are to be omitted due to the presence of a dominant transmission path being a slit. Larger differences occur in the low frequency range, where the sound transmission through the panel still has some meaning. On the other hand, in the range of higher frequencies, the presence of leaks included in the SEA model through non-resonance transmission and leaks included in the simple dependence by spatial averaging of the transmission coefficient result in a similar course of enclosure IL. This means that for the model the precise determination of the transmission coefficient of slits is a crucial factor. The work confirmed that the Mechel's model provides the best prediction of transmission coefficient in case of nar-

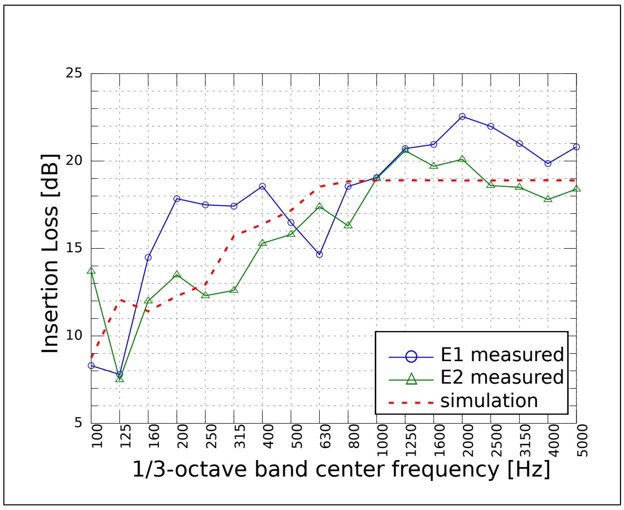

Figure 6. Insertion Loss of enclosures with diffrent volumes (different modal overlaps). Enclosure E2 contains more modes in each frequency band. The graph refers to enclosures with light mineral wool and an leak ratio equal to 1 %, measuring method: RM

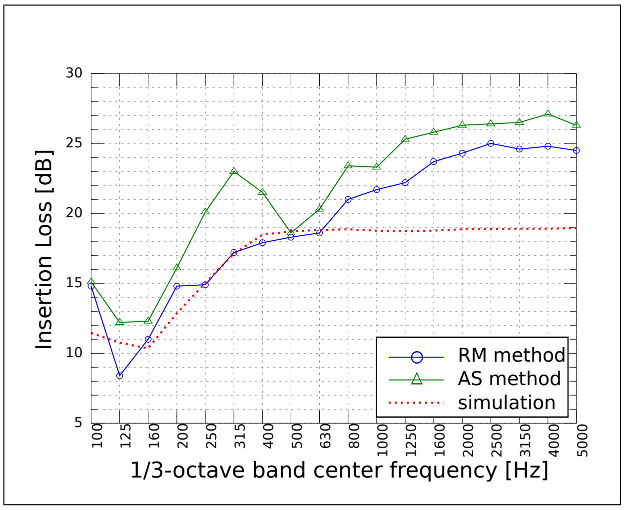

Figure 7. Insertion Loss of enclosures measured with different methods. The graph refers to enclosures with dense mineral wool and an leak ratio equal to 1 %, enclosure E2. The lack of convergence of measurements and simulations above 630 Hz has been explained in section 4.1.

row gaps or for low frequencies. In the case of high gaps, there was a discrepancy between simulations and measurements. Significantly better convergence of simulations and measurements for high gaps was obtained in the case where part of the mineral wool located close to the gaps was cut off. This did not cause the significant decrease in the average absorption coefficient, but it made the approximation of the gap transmission loss with 0 dB more appropriate. In this case, good convergence was also obtained for the enclosures with the largest leaks. Simulated and measured IL values match better with each other in a case of larger enclosure. In the case of a small enclosure, a larger spread of measurement results was observed around the IL curve determined by the models. This result confirms the importance of providing high modal overlap conditions while using statistical models in acoustic simulations. The work showed that the best convergence of simulations and measurements is ensured by the RM measurement method defined by the ISO 11546-1 standard. The tested models did not take into account the influence of the geometry of the source on IL, therefore the method using the microphone inside the enclosure gave better results. This was due to the fact that the microphone disturbs the acoustic field inside the enclosure to a much lesser extent than the much larger omnidirectional source.

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