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Research on the Influence of Airflow Resistance of Layered Porous Structures on the Sound Absorption Coefficient

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Abstract The paper presents the research on the influence of airflow resistance on the sound absorption coefficient of layered porous structures. For the calculation of the sound absorption coefficient, the models of layered sound-absorbing structures were developed with the use of numerical computational models. Using the developed models, optimization was carried out to maximize the average sound absorption coefficient of the structures for a given frequency range. As a result of the research, the dependence of the change in airflow resistance for the successive layers of the material was determined. The results of the work will be particularly useful in the design of wedges used in anechoic chambers.

Keywords: airflow resistance, anechoic wedges, transfer matrix method, optimization, PSO.

1. Introduction

Sound absorption coefficient of porous materials is strictly related to their airflow resistance. Using Delany-Bazley [1] and Miki [2] models, we can determine sound absorption coefficient for a given airflow resistance R_f. However, in the case of designing sound absorbing wedges to be used in anechoic chamber, such an approach may turn out insufficient. Such structures require sound absorption coefficient values to be at least 0.99 in as broad frequency range as possible, the low frequency range being the most important, since it determines the cut-off frequency of the chamber. Figure 1 shows the comparison of three uniform sound absorbing porous materials of three different airflow resistance values, each of them 20 cm thick. Calculations were made using Miki model with the limit of validity $0.01 < f/R_f < 1$, that is R_f should be equal to 5 000 – 10 000 Pa·s/m^2 for the frequency range 100 – 5 000 Hz.

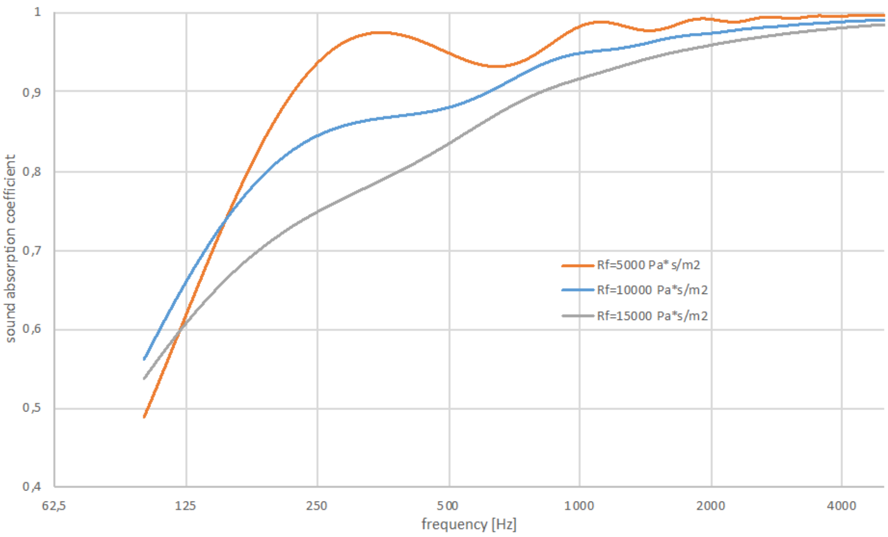


Figure 1. Characteristics of sound absorption for porous, homogeneous materials with flow resistance 5 000, 10 000 and 15 000 [Pa·s/m^2].

The use of homogeneous material is quite simple, but its sound absorption characteristics are strongly wavy at low frequencies (Fig. 1), which unfortunately eliminates such material from use. The solution to this problem may be the use of layered structures with different flow resistances.

2. Modeling of acoustic structures using the Transfer Matrix Method (TMM)

2.1. Description of the method

To determine the parameters characterizing the acoustic properties of the systems, e.g., the sound absorption coefficient α, the transfer matrix method TMM (Transfer Matrix Method) can be used.

When using the TMM method for acoustic analysis, it is assumed that the incident wave is a plane wave perpendicular to the structure and that only a plane wave propagates in its elements. Figure 2 shows the analyzed system consisting of the components (e.g. layers of porous material, changes in the cross-section, etc.).

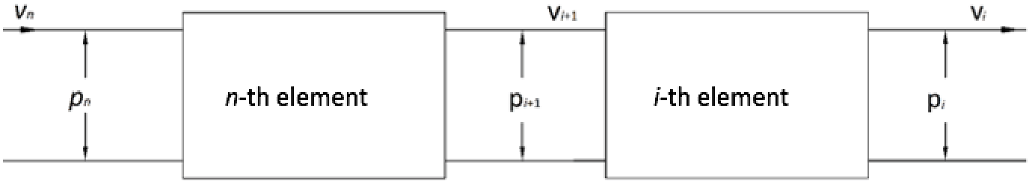


Figure 2. Diagram of sound propagation in elements. Symbols: p_{i+1} – acoustics pressure at the inlet of the element, p_i – acoustics pressure at the outlet of the element.

The values of acoustics pressure p and acoustic velocity v are marked at the boundaries between the individual elements (layers) of the structure. The relationship between the top layer i+1 and the bottom layer can be described as:

$$\begin{bmatrix} p_{i+1} \\ \boldsymbol{v}_{i+1} \end{bmatrix} = \mathbf{T}_i \begin{bmatrix} p_i \\ \boldsymbol{v}_i \end{bmatrix}, \tag{1}$$

where $\mathbf{T}_i$ is the transfer matrix for the ith element. The p and v values for the nth layer can be determined analogously:

$$\begin{bmatrix} p_n \\ \boldsymbol{v}_n \end{bmatrix} = \mathbf{T}_{i+1} \begin{bmatrix} p_{i+1} \\ \boldsymbol{v}_{i+1} \end{bmatrix}, \tag{2}$$

Then substituting the dependence (1) to (2) we get:

$$\begin{bmatrix} p_n \\ \boldsymbol{v}_n \end{bmatrix} = \mathbf{T}_{i+1}\mathbf{T}_i \begin{bmatrix} p_i \\ \boldsymbol{v}_i \end{bmatrix} = \mathbf{T} \begin{bmatrix} p_i \\ \boldsymbol{v}_i \end{bmatrix}, \tag{3}$$

where:

$$\mathbf{T} = \prod_{i=0}^{n-1} \mathbf{T}_{n-i}. \tag{4}$$

T is a replacement matrix for the whole structure which has the following form:

$$\mathbf{T} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \tag{5}$$

For a continuous medium, the transfer matrix **T** takes the form [6]:

$$\mathbf{T}_m = \begin{bmatrix} \cos(k_m l_m) & iZ_m \sin(k_m l_m) \\ {}^{i}/_{Z_m} \sin(k_m l_m) & \cos(k_m l_m) \end{bmatrix}, \tag{6}$$

where: k_m – wave number, l_m – material thickness, Z_m – characteristic impedance.

2.2. Determination of acoustic parameters of systems based on the transition matrix

From the transfer matrix **T**, it is possible to calculate the effective (equivalent) parameters of the entire system, i.e. the wave number:

$$k_{eff} = \frac{1}{L} \cos^{-1}\left(\frac{T_{11} + T_{22}}{2}\right), \tag{7}$$

where L – system thickness, and the specific acoustic impedance:

$$Z_{eff} = \sqrt{\frac{T_{12}}{T_{21}}}. \tag{8}$$

Using the transfer matrix **T**, it is possible to determine the reflection coefficient according to the formula:

$$R = \frac{T_{11} - Z_0 T_{21}}{T_{11} + Z_0 T_{21}}, \tag{9}$$

where: $Z_0 = \rho_0 c_0$, ρ_0 = 1.21 kg/m³ – air density, c_0 = 343 m/s – sound speed in air. As a result, it is possible to determine the sound absorption coefficient:

$$\alpha = 1 - |R|^2. \tag{10}$$

3. Optimization of the sound absorption coefficient of the designed system

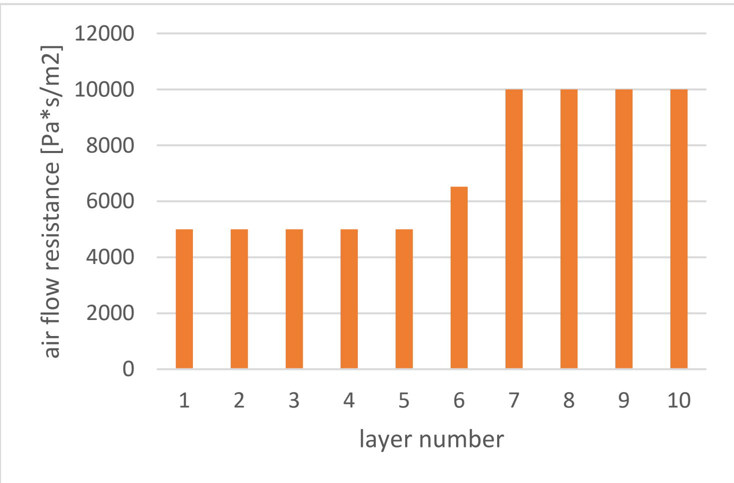
3.1. Description of the PSO method – optimization by means of a swarm of particles

To optimize the sound absorption coefficient of the designed system so that the system adopts the sound absorption coefficient α minimum 0.99 and that the system obtains this value of the coefficient α for the lowest possible frequency, the PSO optimization method (Particle Swarm Optimization) was used [3]. It is a metaheuristic algorithm used to solve optimization problems, i.e. finding the optimal (largest or smallest) value of a certain function.

Its idea is to iteratively search the space of the problem solutions with the help of the so-called swarm of particles. Each particle has its position in the solution space, speed, and direction in which it is moving. The best solution found by each particle (local solution), as well as the best solution of the whole swarm (global solution), is also remembered. The speed of the movement of individual particles depends on the location of the best local and global solution and the speed in the previous steps.

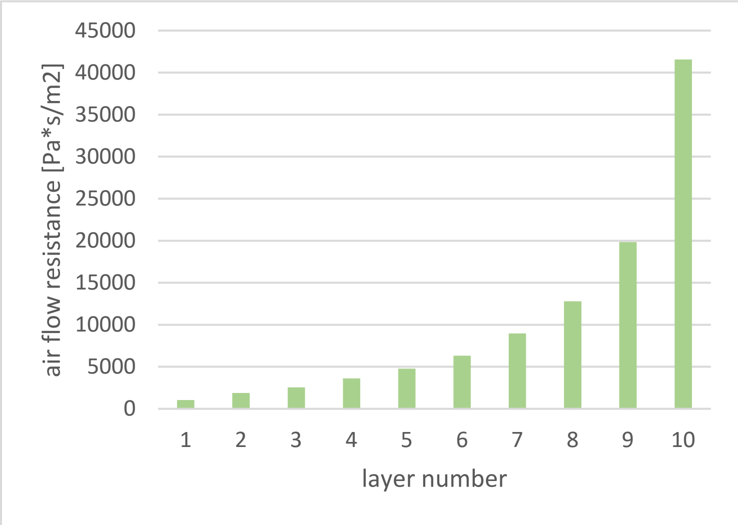
3.2. Model results

Using the PSO method in the MATLAB environment, it was possible to create a model of a sound-absorbing system composed of any number of layers of porous materials and with any values of airflow resistance. The optimization criterion was the achievement of the sound absorption coefficient α at least 0.99 from the lowest possible frequency.



Layer No.	Airflow resistance [Pa·s/m²]
1	5 000
2	5 000
3	5 000
4	5 000
5	5 000
6	6 521
7	10 000
8	10 000
9	10 000
10	10 000

Figure 3. Determined values of airflow resistance for subsequent layers using PSO optimization.



Layer No.	Airflow resistance [Pa·s/m^2]
1	1 055
2	1 877
3	2 543
4	3 620
5	4 786
6	6 324
7	8 959
8	12 794
9	19 841
10	41 569

Figure 4. Determined values of airflow resistance for subsequent layers using PSO optimization.

The model uses 10 layers of porous material, each 2 cm thick. The total thickness of the structure was 20 cm. The range of airflow resistance selection was set in the range from 5 000 to 10 000 Pa·s/m^2 according to Miki model limit of validity.

Figure 3 shows results of airflow resistance for the subsequent layers (layer no 1 is from the sound source) obtained in PSO optimization. Figure 4 shows results obtained in calculation with low airflow resistance limit changed to 1 000 – 50 000 Pa·s/m^2.

The sound absorption coefficient α was determined (Fig. 5) for the optimized values of airflow resistance of successive layers on the basis of the Miki model [2] with the range low limit equal to 1 000 and 5 000 Pa·s/m^2.

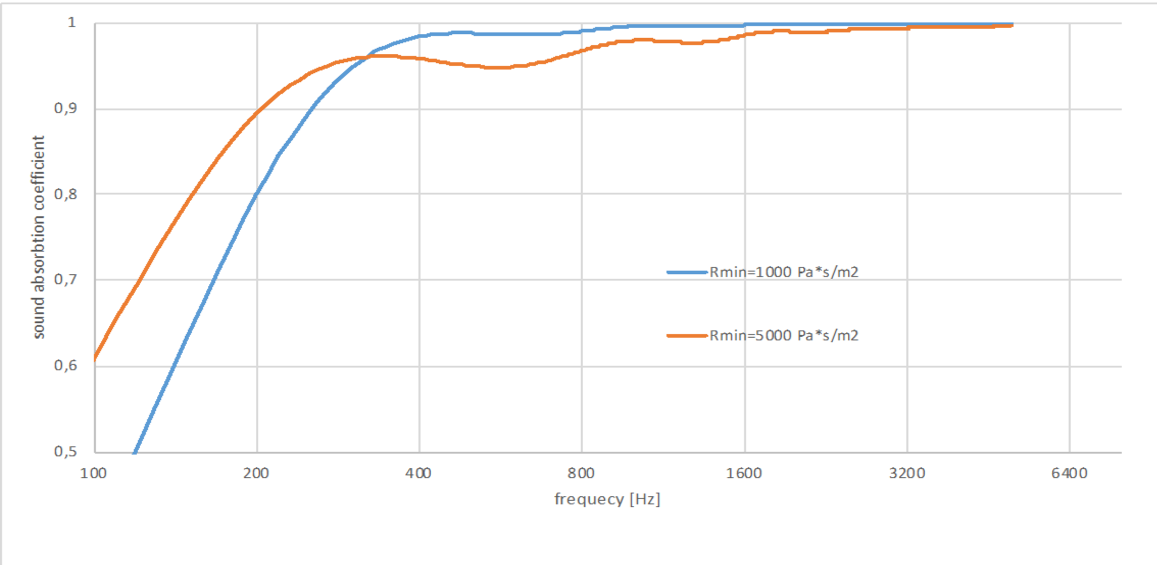


Figure 5. Characteristics of sound absorption of a layered structure based on optimized values of airflow resistance.

4. Verification of the method

In order to verify the proposed layered porous structure, sound absorption coefficient measurements of selected samples were made. Results of the impedance tube measurement (Fig. 8) compared with the results obtained based on the Miki model are presented in Fig. 10. Airflow resistances used in the Miki model were measured in the measurement stand presented in Fig. 6.

4.1. Research on the specific air flow resistance

The tests were performed on a stand for air flow resistance determination in accordance with PN-EN ISO 9053-1 [5]. The flow resistance of two materials was tested – Basotect melamine foam from BASF, approximately 31 mm thick, and glass wool from ISOWER, 50 mm thick. Samples with a diameter of 100 mm were prepared for the tests. The airflow resistance was determined for the melamine foam to be 11 885 Pa·s/m^2, and for glass wool to be 19 659 Pa·s/m^2. Then, the sound absorption coefficient of the discussed materials and the layered structure consisting of melamine foam and glass wool were calculated by the equation (10). Results are presented in Fig. 7.

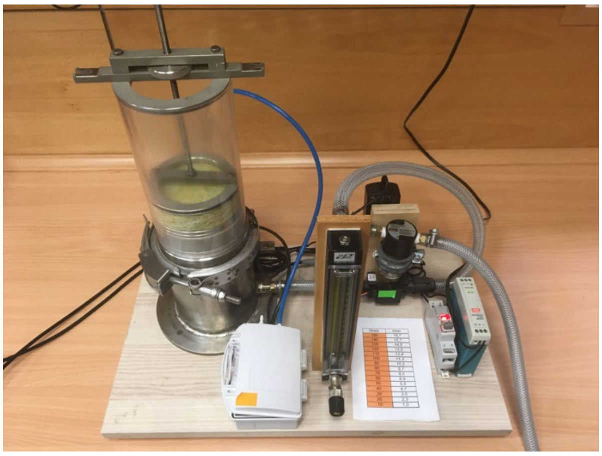


Figure 6. Setup for determining the air flow resistance.

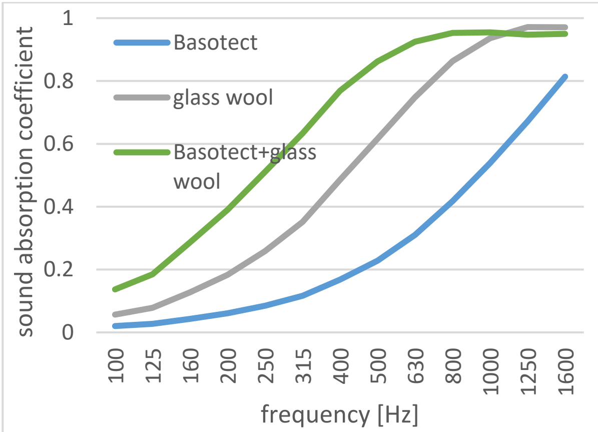


Figure 7. Calculation of the sound absorption coefficient of the samples based on the determined air flow resistance.

4.2. Determination of the sound absorption coefficient in an impedance tube

The tests were carried out in accordance with PN-EN ISO 10534-2 [4] in an impedance tube by Bruel & Kjaer 4206 for the same samples, i.e. melamine foam, glass wool and a system composed of melamine foam and glass wool. Results are presented in Fig. 9.

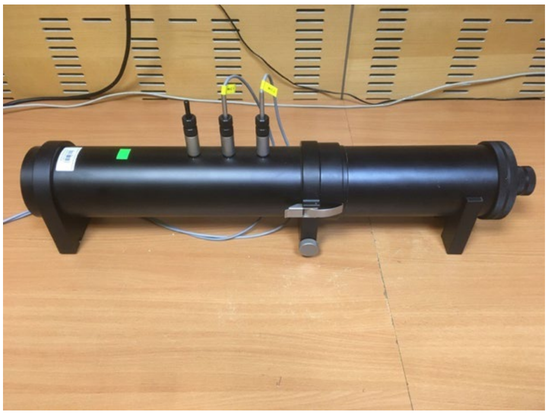


Figure 8. Impedance tube for measuring the sound absorption coefficient.

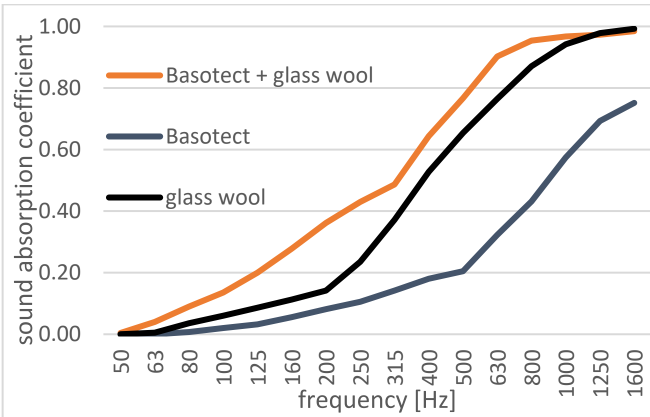


Figure 9. The results of the measurement of the sound absorption coefficient α from the impedance tube.

5. Summary of the results

The results of the impedance tube measurement of the designed structure composed of melamine foam and glass wool were compared with the results of the simulations of the same system. Both characteristics have a similar shape, although in the middle frequency range the simulation results give higher values of the sound absorption coefficient.

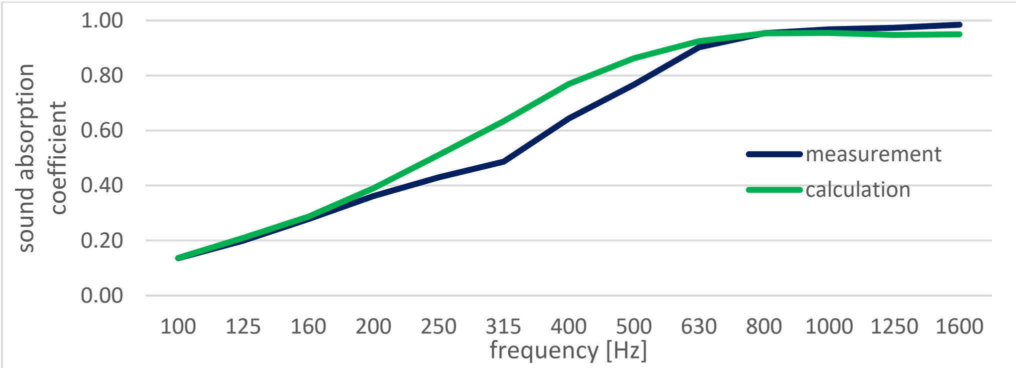


Figure 10. Comparison of the measurement results with the simulation results.

6. Conclusions

The presented method of determining the sound absorption coefficient based on the airflow resistance value gives values close to the values measured in the impedance tube. Appropriate assembly of layered materials significantly improves the sound absorption coefficient of the entire system.

To obtain the highest sound absorption coefficient, the airflow resistance should be as low as possible at the sound source side and then increase gradually.

Additional information

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

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