ONE REALIZATION OF THE SYSTEM FOR MEASURING AIRFLOW RESISTANCE

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Abstract - *Airflow resistance is one of the main non-acoustic parameters, which shows the behaviour of porous materials used in sound-absorbing systems. The standard SRPS ISO 9053 specifies two methods for measuring airflow resistance: a steady-state airflow method and an alternating airflow method. The paper presents the possibility of realization of the measurement system for measuring airflow resistance by using the existing laboratory equipment. The constant airflow is provided by a vacuum pump. The advantage of using this measurement system is a considerably lower price in comparison with commercial solutions, and the procession of measurement results which is not complete automated is seen as the weakness.*

Keywords: *determination of airflow resistance, porous acoustic materials, absorption coefficient*

1. INTRODUCTION

Airflow resistance is a standard value defined as the ratio between the pressure drop and the volumetric airflow rate through a test sample. The standard ISO 9053 specifies the procedure and the principle sketch of the steady-state method. The calibrated differential pressure gauge and the volumetric airflow rate metre are the most important measuring instruments in the system for measuring airflow resistance. The airflow source must create a sufficiently small air velocity so that the measured airflow resistance could not depend on air velocity. In the steady-state method, airflow resistance is determined for the airflow velocity of 0.5 mm/s in the measuring cell. The equipment used for measuring differential pressure must allow measurement of low pressures of 0.1 Pa.

Standard methods require special instruments which are available only in specialised laboratories. Taking this circumstance into account, the authors describe a solution of the measurement system for measuring airflow resistance of porous materials. Its application requires the measuring instruments and equipment available in most laboratories for fluid technique and acoustics. Only the measuring cell was specially made for the needs of measuring airflow resistance of porous materials.

The final aim of these measurements is determination of the sound absorption coefficient in porous materials. By measuring airflow resistance for porous materials, the sound absorption coefficient can be determined depending on the frequency for different densities and thicknesses of porous materials. For manufacturers of sound absorbing materials and designers of noise protection systems, it is important that they have the possibility to estimate sound absorption on the basis of their knowledge of structural and mechanical properties of those materials.

2. METHODS FOR DETERMINATION OF AIRFLOW RESISTANCE

Measurement systems for determination of airflow resistance allow testing samples for the purpose of research and development of porous absorbing materials as well as quality control of these materials in the production process. The standard SRPS ISO 9053 foresees two methods for measuring airflow resistance, as it is shown in Figure 1.
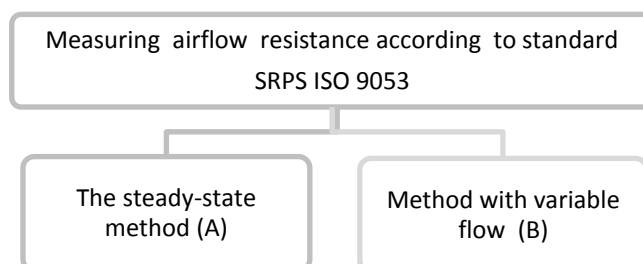

Fig. 1 *Methods for measuring airflow resistance*

The air which has a definite velocity and volumetric flow rate laminarly flows through the surface of the sample made of porous material. The difference in pressure is measured on the front and rear sides of the sample. The schematic presentation of the measuring process is shown in Figure 2.
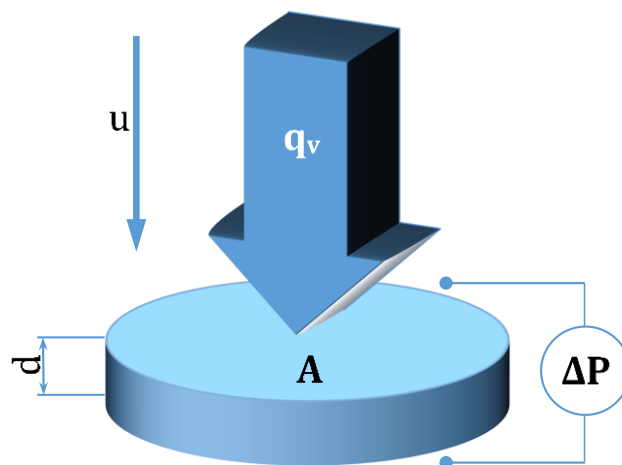

Fig. 2 *Schematic presentation of measuring airflow resistance*

The airflow resistance represents the ratio between the difference in pressure and the volumetric flow rate.

$$R = \frac{\Delta p}{q_v} \left[\frac{Pa \cdot s}{m^3} \right] \qquad (1)$$

where:

Δp – the difference in air pressure in front and behind the test sample in relation to the atmosphere, in Pascal

q_v - the (volumetric) airflow rate through the test sample, in cubic metres per second

In acoustics, the specific airflow resistance (Rs) is used more frequently, and it actually represents the acoustic impedance. The specific airflow resistance (Rs) is particularly useful for comparing acoustic materials because it does not depend on the area. Variations in material thickness and pore size will change the value of specific airflow resistance.

The specific airflow resistance is calculated according to the expression:

$$R_s = R \cdot A \left[\frac{Pa \cdot s}{m} \right] \qquad (2)$$

where:

R_s – the airflow resistance of the test sample, in Pascal seconds per metre

A – the area of the cross section of the test sample normal to the direction of flow, in square metres

The airflow resistivity is the value which is suitable for selection of thickness of the absorbing material. It is particularly important for open-cell foam materials because they can be manufactured in a lot of different thicknesses. The airflow resistivity is determined according to the expression:

$$r = \frac{R_s}{d} \left[\frac{Pa \cdot s}{m^2} \right] \qquad (3)$$

where:

R_s – the specific airflow resistance of the test sample, in Pascal seconds per metre

d – the thickness of the test sample in the direction of flow, in metres

2.1 Method of calculation of the sound absorption coefficient

The standard EN 12354-6: 2003 recommends the calculation of the diffuse sound absorption coefficient of porous materials. For a diffuse acoustic field, the absorption coefficient α_s can be determined as:

$$\alpha_s = \int_0^{\pi/2} \alpha_\varphi \sin 2\varphi \, d\varphi \qquad (4)$$

$$\alpha_\varphi = 1 - \left| \frac{Z'\cos\varphi - 1}{Z'\cos\varphi - 1} \right|^2 \qquad (5)$$

$$Z' = Z_c' \coth \gamma d \qquad (6)$$

where:

φ - the angle of incidence, in radians

α_φ - the absorption coefficient for a plane sound wave, incident at an angle φ

Z'- $\rho_0 c_0$ – the normalized surface impedance of the layer

Z_c'- $\rho_0 c_0$ – the normalized characteristic impedance of the absorbing material

γ - the propagation coefficient in the absorbing material, in radians/m

d – the thickness of the layer, m

The normalized characteristic impedance Z_c' and the propagation coefficient γ can be determined if the specific flow resistance of porous materials r is known using theoretical models:

Table 1 *Models for calculation of the absorption coefficients of fibrous and open-cell foam materials*

A. Delaney & Bazley's relationships (for fibrous material)		B. Duun & Davern's relationships (for open-cell foams)	
$Z_c' = \left(1 + 0.0571 \cdot C^{0.754}\right) - i\left(0.087 \cdot C^{0.732}\right)$	(7)	$Z_c' = \left(1 + 0.114 \cdot C^{0.369}\right) - i\left(0.0095 \cdot C^{0.758}\right)$	(9)
$\gamma = k_0\left(0.189 \cdot C^{0.595}\right) + ik_0\left(1 + 0.0978 \cdot C^{0.7}\right)$	(8)	$\gamma = k_0\left(0.168 \cdot C^{0.715}\right) + ik_0\left(1 + 0.136 \cdot C^{0.494}\right)$	(10)

where:

$$C = \frac{r}{\rho_0 f} \qquad (11)$$

r – the airflow resistivity, [Pa·s/m^2]

f – the frequency [Hz]

ρ_0 - the density of air, [kg/m^3] (≈ 1.2 kg/m^3)

3. THE STEADY-STATE METHOD

The method is based on the passage of one-way airflow through the test sample in the form of a circular cylinder or a rectangular parallelepiped and measuring of the resulting pressure drop between two free surfaces of the sample.
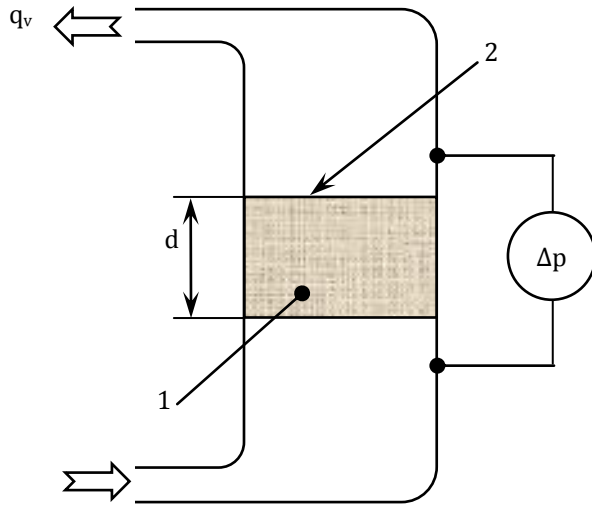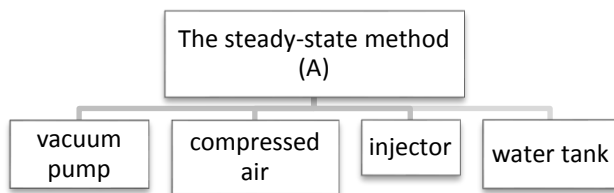

1. Porous material – sample
2. Cross section (area – A)

q_v – Volumetric airflow rate
d – Sample thickness
Δp – Change in pressure

Fig. 3 *Steady-state method (method – A) – Basic principle*

Depending on the way of airflow supply, the steady-state method can be realized in several ways. Airflow can be created by: a vacuum pump, compressed air, a water tank and an injector (Fig. 5).

Fig. 4 *Ways of airflow supply in the steady-state method*

3.1 Test samples

The shape of the sample can be circular or rectangular. In our case, the measuring cell is of a circular cross section, which results in the shape of the sample. When soft, compressible materials, such as fibrous and open-cell foam materials are tested, in preparation of samples the possibility of air leakage along their edges must be reduced as much as possible. This problem is solved by preparing samples whose sides are a little longer than the measuring cell. Samples made of rigid material must have the same dimensions as the measuring cell.

As for the thickness of samples, the holder of samples must be equipped with a micrometre or another indicator which measures the thickness of samples with the accuracy of ±2.5% of the specified value. The thickness of the test sample is chosen in such a way to obtain a measurable pressure drop. If test samples are of insufficient thickness to create a measurable pressure drop, the test samples can be piled up, five samples at the most. The piled samples must be selected in the same manner.

The number of test samples must be taken from at least three products and from each of them three trial samples for testing must be cut out.

3.2 Test procedure

1. The test sample is placed in the measuring cell
2. It should be checked whether the edges are well sealed. For fibrous and open-cell foam absorbing materials, most frequently no additional sealing is necessary. For sealing rigid samples, sealing which can be performed by applying different sealing materials can be provided. The standard recommends bitumen-based masses. As for the selection of the sealing mass, easy removal of the mass after sealing should be allowed in order not to prevent further measurements by its presence on the walls of the measuring cell. Besides, attention should be paid to the time necessary for hardening of the mass and what can be used to remove it from the walls of the measuring cell. Scratching of the hardened sealing mass can damage the wall of the measuring cell. The use of additional chemical agents for removal of the sealing mass slows down the measuring process and leads to unnecessary costs. Therefore, depending on the material of the sample, it is important to determine the sealing material which can easily be deposited and removed.
3. If the thickness of the test sample is not known, the measuring device which is an integral part of the measuring cell measures the thickness in the so-called free state of the sample where the sample is just lightly touched by means of a piston with the grid.
4. The thickness of the samples is recorded and this measurement is used for determination of the volume in free state.
5. The measuring cell is designed in such a way to allow measuring airflow resistance in the samples made of fibrous and open-cell foam materials, whose thickness can be changed. The change of thickness is performed by the pressure exerted by the piston with the grid and by fixing the piston, which makes the sample remain in a compressed state.
6. The thickness of the sample is recorded and this measurement is used for determination of the volume in compressed state.
7. As specific airflow resistance in a lot of absorbing materials increases with the increase in air velocity in a certain range of velocities, it must be measured at the lowest air velocity. For the lower limit, the recommended air velocity is $0.5 \cdot 10^{-3}$ m/s. This value of particle velocity corresponds to the sound pressure of 0.2 Pa.

4. AN EXAMPLE OF REALIZATION OF THE SYSTEM FOR MEASURING AIRFLOW RESISTANCE

The steady-state method, in which airflow is provided by means of a vacuum pump, was selected for measuring airflow resistance. This method is based on the passage of one-way airflow through the test sample in the form of a circular cylinder or a rectangular parallelepiped and measuring the resulting pressure drop between two free surfaces of the sample (Fig. 5).

1. Sample Holder
2. Sample
3. Manometar
4. Filter
5. Flow Regulator
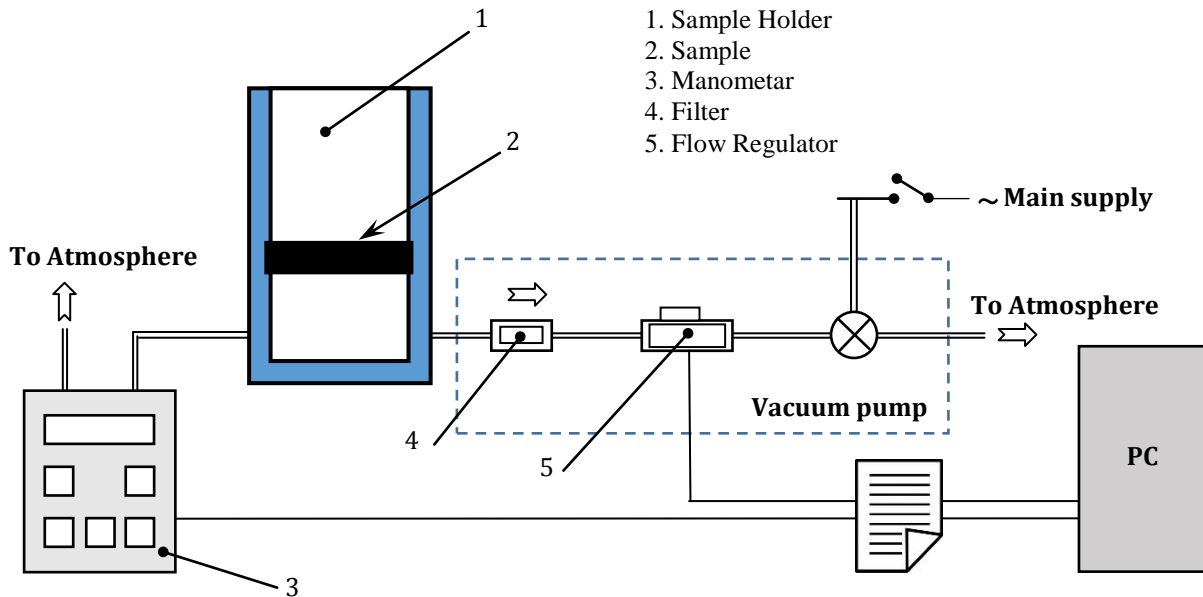
Fig. 5 *Block diagram of the steady-state airflow system*

The structure of the measurement system which uses the steady-state method, which is provided by means of a vacuum pump, is presented in the block diagram in Figure 5.

The vacuum pump make ZAMBELLI, type ZB1, is used as the device for creation of airflow. The pump is of a small weight (7 kg) and therefore it is suitable both for laboratory and field measurements. The pump is of a membrane type and can realize the maximum free flow of 30 l/min. The underpressure produced by the pump is higher than 0.773 bar (580 mmHg). The pump has two airflow metres, which operates on the principle of the ball rotametre. Smaller airflows in the range of 0.2÷6 l/min are measured by means of the smaller rotametre, and higher flows in the range of 5÷30 l/min are measured by means of the bigger rotametre. The maximum flow measurement error is ± 2%. The pump allows the fine control of flow and the stability of flow in the part of the measuring cell which is behind the sample. By its characteristics, the pump provides a sufficiently small air velocity so that the measured airflow resistance could not depend on air velocity. The pump enables airflow velocity of $0.4 \cdot 10^{-3}$ m/s in the measuring cell, which completely corresponds to the recommendations from the standard SRPS ISO 9053 ($0.5 \cdot 10^{-3}$ m/s).

In the measuring cell, the atmospheric pressure is on one side of the sample, and the underpressure produced by the vacuum pump is on the other side of the sample. In order to provide conditions for maintaining underpressure, the measuring cell must be well sealed on one side. The differential pressure gauge TESTO 512 is used for measuring the difference in pressures on both sides of the sample. This gauge has a measuring range of 0 to 200 Pa with the resolution of 0.1 Pa. The equipment used allows measurement of differential pressure up to the accuracy of ±5% of the specified value.

The measuring cell has the form of a circular cylinder, and it is made of plexiglass so that placing of the sample could be visually monitored. The inner diameter of the measuring cell is 100 mm, which satisfies the requirement of the standard SRPS ISO 9053 that the inner diameter must be longer than 95 mm.

**Fig. 6** *Look of the realized measurement system for determination of airflow resistance*

The height of the cell is 300 mm so that the airflow which gets in and out from the test sample could be laminar. The height of the measuring cell should be by at least 100 mm bigger than the thickness of the sample. The test sample must be placed in the measuring cell, above and at a sufficient distance from the cell base to achieve the above mentioned requirements. The sample support should have uniformly distributed openings across at least 50% of its surface. The minimum diameter of the opening is also prescribed (3 mm).

The minimum percent of opening is prescribed in order not to limit airflow through the sample. The airflow resistance in such elements (measured with the air velocity higher than the highest velocity used for testing samples) must be smaller than 1% of the airflow resistance measured while testing the samples.

The measuring cell is placed at the flange which can be fastened to the holder of the measuring cell either horizontally or vertically. The measuring cell can also be used without its fastening to the holder, so that it is suitable both for field work and directly in the production process and inspection of acoustic materials.

4.1 Test conditions

In case of the procedure which uses constant airflow, the pressure drop Δp can be measured either directly at the velocity of 0.5 mm/s or gradually by its reducing to the lowest limit of air velocity. At a gradual reduction of air velocity, a graphical presentation of specific airflow resistance as a function of air velocity is given for each sample. Specific airflow resistance at the flow velocity of $0.5 \cdot 10^{-3}$ m/s is determined from the diagram, by averaging or, if necessary, by extrapolation.
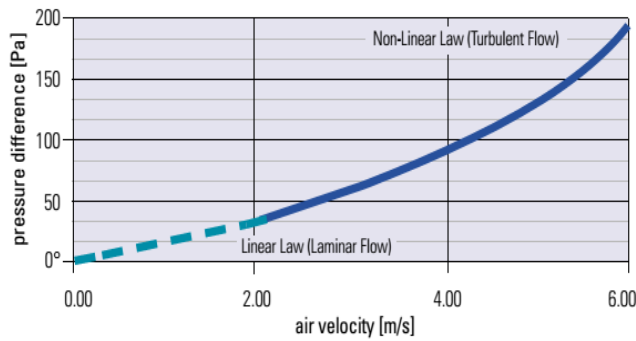
Fig. 7 *Airflow resistance – test conditions: linear and non-linear* [6]

In order to perform accurate measurement of airflow resistance, airflow must be linear and cannot be provided by typical equipment which does not have the possibility of adjusting very small flows.
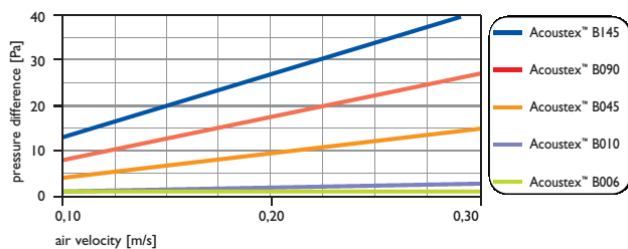
Fig. 8 *Dependence of the pressure drop for different types of materials* [6]

Certain renowned world manufacturers of acoustic materials (such as SaatiTech) perform measurement of specific airflow resistance at low pressures (tolerance up to 0.1 Pa) and air velocities of 0.3 m/s (Figure 8).

4.2 Measurement results and their procession

Measurement results are written in the database on a paper or can be directly entered in an Excel sheet. The sheet contains input and output data. The input data can be divided into two groups. The first group is made of the data whose value is constant because they relate to design parameters of elements of the measurement equipment or the sample. An example of data belonging to this group is: sample diameter, diameter of the hose for the vacuum pump air and diameter of the measuring cell. The second group consists of data whose values are variable. This group includes data about the selected volumetric flow rate and the measured pressure drop. The output data represent the calculated values of airflow resistance, specific airflow resistance and airflow resistivity.

In order to determine specific airflow resistance, it is necessary to select 10 values of volumetric flow rate and for them measure the pressure drop through the sample. It is necessary to reduce the laminar airflow velocity to the value of 0.5 mm/s, if it is allowed by the pump flow. Namely, at the lowest airflow, the pressure drop must be measurable. If it is not possible to measure the pressure drop at the limit vale of airflow velocity of 0.5 mm/s, the value of specific airflow resistance is determined by extrapolation.

**Table 2** *Input and output data at the concrete sample in the procedure of measuring airflow resistance*

q_v	Δp	u	R	R_s	r
[lit/min]	[Pa]	[mm/s]	[Pa·s/m^3]	[Pa·s/m]	[Pa·s/m^2]
20	3.3	42.4	9900	77.8	3887.7
17	2.4	36.1	8470.6	66.5	3326.4
15	2	31.8	8000	62.8	3141.6
12	1.5	25.5	7500	58.9	2945.2
11	1.2	23.3	6545.5	51.4	2570.4
10	1	21.2	6000	47.1	2356.2
9	0.9	19.1	6000	47.1	2356.2
8	0.8	17	6000	47.1	2356.2
7	0.7	14.9	6000	47.1	2356.2
6	0.5	12.7	5000	39.3	1963.2

For the sponge sample made of polyurethane foam, density 25 kg/m^3, specific airflow resistance was determined to be 26.2 [Pa s/m]. Determination of this value is presented in the diagram (Figure 9). The linear regression line was obtained on the basis of 10 values of airflow within the range of 20÷6 [l/min]. After determination of the linear regression equation, the value of airflow resistance for the velocity of 0.5 mm/s was determined by extrapolation. Based on the value of the Pearson correlation coefficient (R=0.978), it can be seen that the correlation between specific airflow resistance and flow velocity is very high.
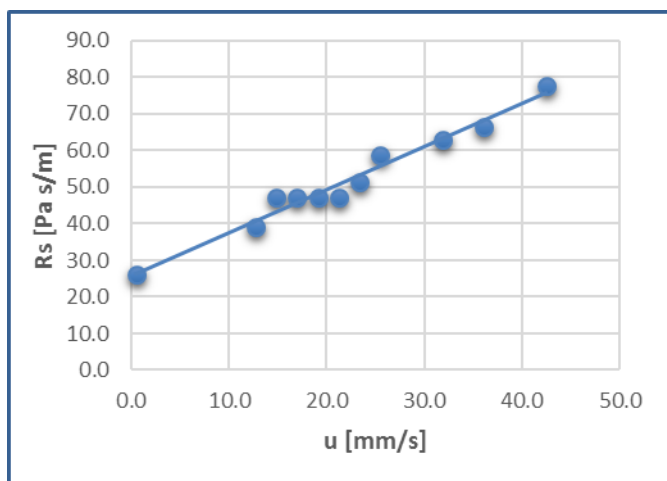
Fig. 9 *Dependence of the specific airflow resistance on the flow velocity*

The final aim of such measurements is to obtain the dependence of the absorption coefficient on the frequency. For the mentioned sponge sample, according to the Duun & Davern's model (9; 10), for open-cell foam materials, the sound absorption coefficient was determined and presented in the form of diagram in Figure 10.
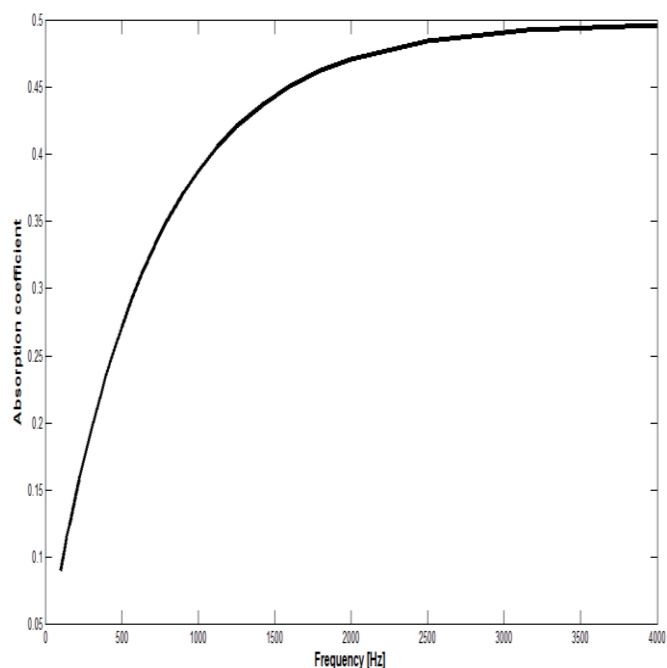
Fig. 10 *Sound absorption coefficient depending on the frequency*

The aim of the paper was to present an engineering solution of a measurement system for determination of airflow resistance. Therefore, the discussion related to the obtained measurement results is in the second plan.

5. CONCLUSION

The method of determination of airflow resistance allows fast estimation of the values of the sound absorption coefficient in porous materials. This method is defined by the standard SRPS ISO 9053:1994, which makes practical realization of the measurement system easier. Commercial solutions are rather expensive, so that the measurement system was designed by using the existing laboratory equipment. After a successful engineering realization of the measurement system for determination of the airflow resistance, it can be concluded that other measurement methods may also be realized by using the existing laboratory equipment, which results in huge financial saving. One of the obstacles toward that goal is the lack of information about the existing measurement equipment both in scientific-research institutions and at the state level. The realized engineering solution of the measurement system can be used both for measurements for scientific-research purposes and for quality control of acoustic materials in the production process. The next step in the research is validation of the measurement results obtained by this method by comparing the measuring values with the measurement results obtained by other methods.

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