EPJ Web of Conferences **321**, 01011 (2025) https://doi.org/10.1051/epjconf/202532101011
APITECH-VII-2025

Creation of an "interferometer" installation at MAI to study the acoustic properties of sound-absorbing materials and liners

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Abstract. An "interferometr" installation with a normal incidence of sound waves has been created in the laboratory of "Vibroacoustics and acoustic design of aviation technology" at MAI to study the acoustic characteristics of sound-absorbing materials and structures. The equipment and main characteristics of the created installation are not inferior to the leading analogues of Bruel&Kjaer, BSWA, Mecanum, Acoustic Awareness, Müller-BBM Industry Solutions GmbH, as well as previously developed and used in the Russian Federation. A comparison was made of the acoustic characteristics of samples of sound-absorbing structures and materials similar in geometric parameters, obtained at the MAI "interferometer" installation and data published in the open press.

1 Introduction

Currently, sound-absorbing structures (SAS) and materials [1,2] are actively used to reduce noise levels in the cabin of aircraft [3,4] and community engine noise [5-7]. Experimental studies of the acoustic characteristics of the SAS and materials are performed on installations of the "interferometer" type with a normal incidence of sound waves. In installations of this type, studies of the influence of sound pressure levels on the sample surface, the spectral characteristics of the noise source and the geometric parameters of the structure on the impedance and sound absorption coefficient are carried out on model samples.

Semi-empirical models [8,9], based on a simplified description of physical processes, are used to calculate the acoustic characteristics of SAS and materials are not universal, and often a certain calculation model works only for a certain type of SAS. Calculating the acoustic characteristics of SAS using numerical modeling [10-13] is a time-consuming and energy-intensive task requiring computing power and taking into account a variety of physical processes. Accordingly, the experimental study of SAS and materials in "interferometer" installations remain a reliable and fast way to determine acoustic characteristics.

"Interferometer" installations with a normal incidence of sound waves implementing the classical two-microphone method of eduction the impedance of structures [14] are widely used by various organizations to determine the acoustic characteristics of sound-absorbing materials and structures [4,15,16].

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This article is devoted to the creation of an “interferometer” installation with a normal incidence of sound waves in the laboratory of "Vibroacoustics and acoustic design of aviation technology” at MAI. The paper discusses the issues of choosing the main geometric parameters of an impedance tube, and also presents the results of preliminary verification of the installation based on comparing the results obtained at the installation with data published in open access.

2 Materials and methods

The general types of interferometers with normal incidence of sound waves from various companies and research institutes are shown in Figure 1.

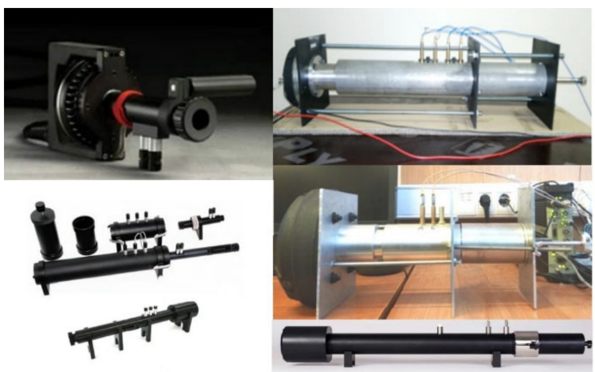


Fig. 1. General types of impedance tubes from various companies and research institutes.

The design of an impedance tube begins with the selection of basic geometric parameters according to ISO 10534-2, providing a given frequency range of measurements. The geometric parameters of the impedance tube were selected in such a way as to ensure reliable measurement results in the frequency range no worse than those of similar installations of 500-6400 Hz.

$$f_l < f < f_u, \tag{1}$$

In this expression f_l - the lower working frequency of the tube, f - the operating frequency range of the pipe,f_u- the upper working frequency of the tube.

The upper working frequency of the tube should ensure the cut-off of the first azimuth mode:

$$f_u < 0{,}58\,\frac{c_0}{d}, \tag{2}$$

c_0 -the speed of sound, d - diameter of the designed tube.

The upper working frequency of the tube is also influenced by the distance between the microphones, therefore it is necessary to ensure it in such a way that half of the wavelength of the corresponding frequency fits between the microphones:

$$f_{u2} < 0{,}45\,\frac{c_0}{s}, \tag{3}$$

To avoid the error of the analysis system, as a rule, the distance between the microphones should exceed 1.5% of the wavelength corresponding to the lower working frequency of the tube:

$$f_l = 0.015\,\frac{c_0}{s}, \tag{4}$$

The length of the tube plays an important role in the design - the distance from the sound source to the sample of the SAS. According to the recommendation from the standard ISO 10534-1 for the standing wave method, a half-wave corresponding to the lower working frequency of the tube should be placed at a distance L, i.e.

$$f_{l2} = 0{,}5\frac{c_0}{L}. \quad (5)$$

Taking into account that the "interferometer" will be used to study various materials and samples of the SAS, including the asymmetric type, according to ISO 10534-2, the distance between the first microphone and the sample should be at least 2 calibers of the impedance tube, i.e.

$$x_2 > 2D. \quad (6)$$

Usually, an acoustic driver, in addition to plane waves, creates non-planar waves that attenuate at a distance of a maximum of three tube diameters, so the distance $L - x_1$ between the sound source and the nearest microphone to it must fulfill the following condition:

$$L - x_1 > 3D. \quad (7)$$

Based on the above, an "interferometer" installation was designed to study the acoustic characteristics of sound-absorbing materials and structures, the dimensions of which are shown in Figure 2. The diameter of the tube channel is 30 mm, and the wall thickness is 7.5 mm. At the speed of sound of 343 m/s, the interferometer, according to formulas (2)-(5), has the following frequency parameters: f_u=6631 Hz, f_{u2}=7716 Hz, f_l=257 Hz, f_{l2}=286 Hz, and also satisfies conditions (6)-(7).

Thus, the "interferometer" design makes it possible to determine the acoustic characteristics of sound-absorbing materials and structures using the 2-microphone transfer function method in the frequency range of 300-6600 Hz.

In a fully equipped and operable form, the MAI interferometer is a universal installation that allows measuring the acoustic characteristics of samples of sound-absorbing materials and structures. Diagram of the designed installation is shown in Figure 2, and general view of the MAI "interferometer" installation in full configuration is shown in Figure 3.

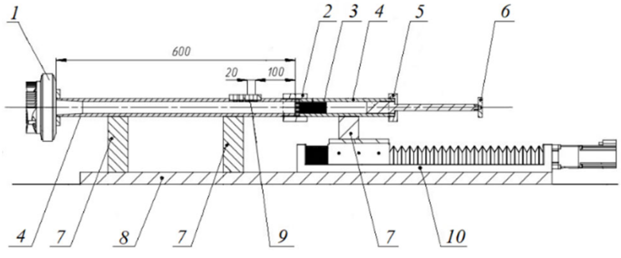


Fig. 2. Diagram of MAI interferometer: 1 - loudspeaker; 2 – coupling; 3 – sample of SAS; 4 – parts of the impedance tube; 5 – cover; 6 – piston with rod; 7 – stands for rigid fastening of parts of the impedance tube; 8 – base plate; 9 – seats (up to 4) for 1/4-inch pressure measuring microphones; 10 – line actuator, including a linear displacement module and a control unit.

The designed device works as follows. The sample for the study is installed in the tube holder - 2. On the personal computer – 1, the necessary coordinates are set for the smooth joining of the two parts of the impedance tube into a single whole. The coordinates are transmitted to the linear actuator control unit – 8. The servo motor, receiving data from the linear actuator control unit, drives the linear displacement module – 7. The part of the impedance tube located on the linear displacement module smoothly connects with the second part of the impedance tube, ensuring sample compression. The end of the piston with the rod is manually smoothly brought to the base of the sample. The rigid connection of the two parts of the tube is provided by a coupling.

After joining the two parts of the impedance tube into a single whole, further operation of the interferometer is standard: loudspeaker – 4 emits the test sample with a given sound signal, microphones – 6 measure acoustic pressure at specified points in the channel of the impedance tube, a recorder – 3 is used to process the acoustic signal.

Fig. 3. General view of MAI interferometer installation (impedance tube) with normal incidence of sound waves for studying the acoustic characteristics of sound-absorbing materials and structures: 1 – personal computer, 2 – impedance tube of 30 mm in diameter inside which the test sample is located, 3– recorder type Ecophysics-500, 4 – loudspeaker with frequency range 0.5 – 20 kHz, 5 - power amplifier with built-in generator, allowing you to set sound pressure levels up to 160 dB, 6 - four ¼ inch pressure microphones with preamplifier (frequency range 1.6–20000 Hz, sensitivity 50 mV/Pa), 7 – linear actuator, 8 – control unit.

To determine the acoustic characteristics of sound–absorbing structures and materials: the real part of the impedance – ReZ, the imaginary part of the impedance – ImZ and the sound absorption coefficient - α; a standardized two-microphone method described in the ISO 10534-2 was implemented on an "interferometer" installation with a normal incidence of sound waves. The essence of the method is that only a plane sound wave propagates in the channel (Figure 4).

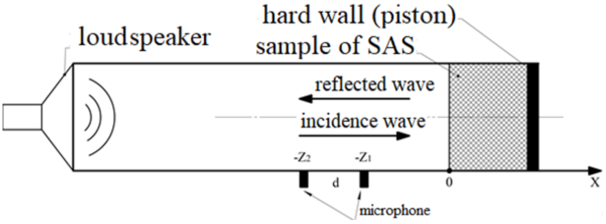


Fig. 4. Diagram of the internal channel of the "interferometer" installation.

The acoustic pressure (p(z)) at any point of the channel can be represented as the sum of two plane waves, incidence and reflected:

$$p(z) = Ae^{ikz} + Be^{-ikz}. \quad (8)$$

To find the unknown amplitude coefficients A and B, it is enough to measure the acoustic pressure at two points:

$$p(z_1) = Ae^{ikz_1} + Be^{-ikz_1},$$
$$p(z_2) = Ae^{ikz_2} + Be^{-ikz_2}. \quad (9)$$

The transfer function (H12) between the microphones is :

$$H_{12} = \frac{p(z_2)}{p(z_1)}. \quad (10)$$

The sound reflection coefficient (R), which is the ratio of the amplitude coefficients of the reflected and incident waves, is determined according to the expression:

$$R = \frac{B}{A}. \quad (11)$$

Formulas (9) are transformed using (7) and (8):

$$R = \frac{H_{12} - e^{-ik(z_1 - z_2)}}{e^{ik(z_1 - z_2)} - H_{12}} e^{2ikz_1}. \quad (12)$$

The formula for calculating the impedance has the form:

$$Z = \frac{1+R}{1-R}. \tag{13}$$

The formula for calculating the sound absorption coefficient has the form:

$$\alpha = 1 - |R|^2. \tag{14}$$

For convenience, dimensionless impedance is used, normalized to the wave resistance ρ0c0:

$$Z_N = \frac{Z}{\rho_0 c_0}, \tag{15}$$

ρ0 – the density of the air.

A distinctive feature of the installation designed at MAI from analogues of well-known world manufacturers and installations created in the Russian Federation is that a linear actuator is used in the design, thanks to which the invention receives a number of advantages: reducing the operator's labor intensity and ensuring repeatability of experimental results (reducing the spread of experimental data).

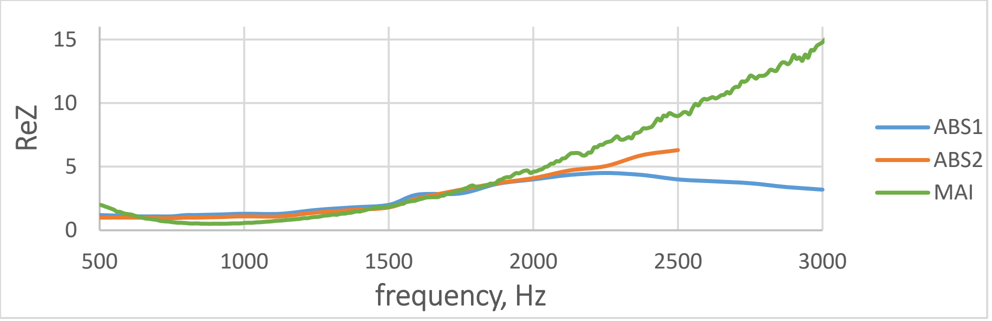
3 Results and discussion

Any invention requires certain settings during manufacture and has its own unique characteristics, the accuracy of the experimental data obtained depends on the correct consideration of which. Therefore, a comparative analysis of experimental data on installations of the “interferometer” with a normal incidence of a sound wave is necessary in order to validate the developed interferometer and the possibility of further application for studies of the acoustic characteristics of SAS and materials. The analysis of experimental data should be carried out on the basis of comparing the measurement results of identical geometric parameters of the samples of the SAS. The results of PNRPU work [17] carried out on an interferometer with normal wave incidence on samples of models A1, A2 and A3 were used as data for comparative analysis. The samples shown in Figure 5 were made by 3D printing with the following geometric parameters: the height of the inner cavity – 10 mm, the height of the hole - 28 mm, the diameter of the inner cavity - 28 mm and the diameter of the hole – 3 mm, 5 mm or 8 mm. During the experiment, a signal of the "white noise" type was set at the level of 100 dB.

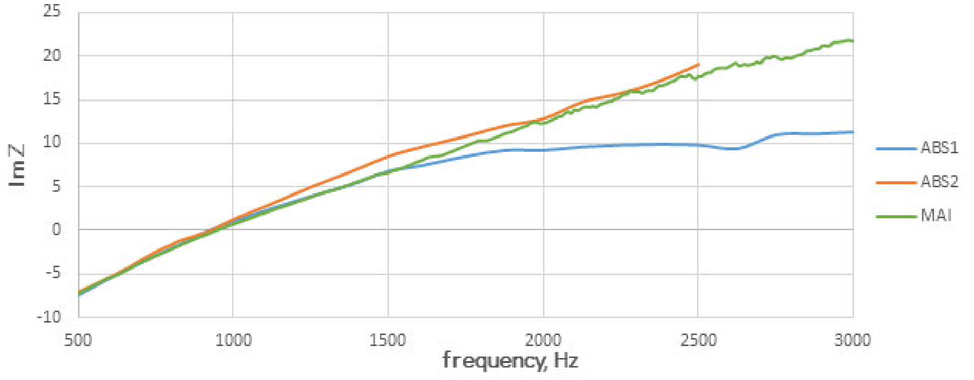
Fig. 5. Samples of SAS for the initial verification of the “interferometer” installation.

According to the results of experimental studies for each sample, the dependences of the real and imaginary parts of the impedance and the sound absorption coefficient on the frequency were obtained, the data are shown in Figures 6-8.

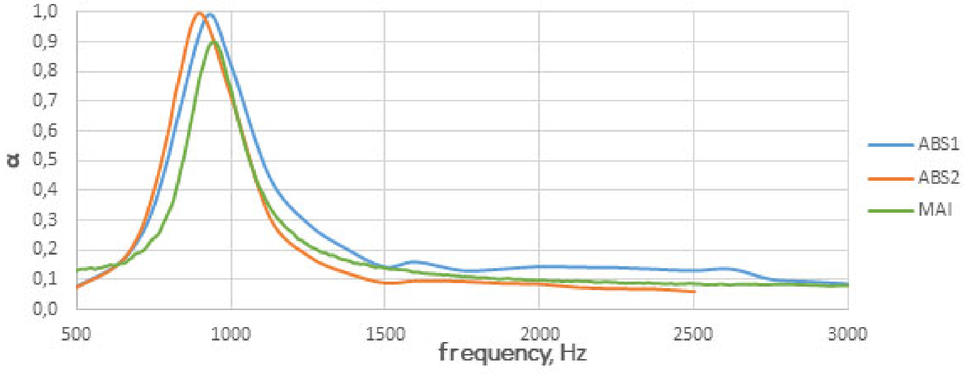
A comparative analysis of the acoustic characteristics during measuring in the laboratory of "Vibroacoustics and acoustic design of aviation technology" of MAI and the data presented in Ref. [17] shows that the imaginary parts of the impedance of the SAS practically coincide, especially on a sample with an 8 mm hole. The real part of the impedance in a wide frequency range has good convergence, and discrepancies at frequencies up to 1 kHz can be caused by the use of various technologies in 3D printing, shrinkage of the material, the variety of plastic used in the manufacture of samples, as well as some features of impedance tubes and the methods used for impedance eduction.



a) real part of the impedance (ReZ)

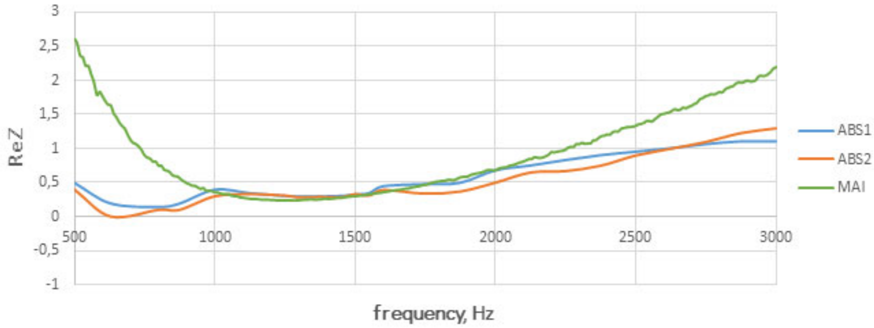


b) imaginary part of the impedance (ImZ)

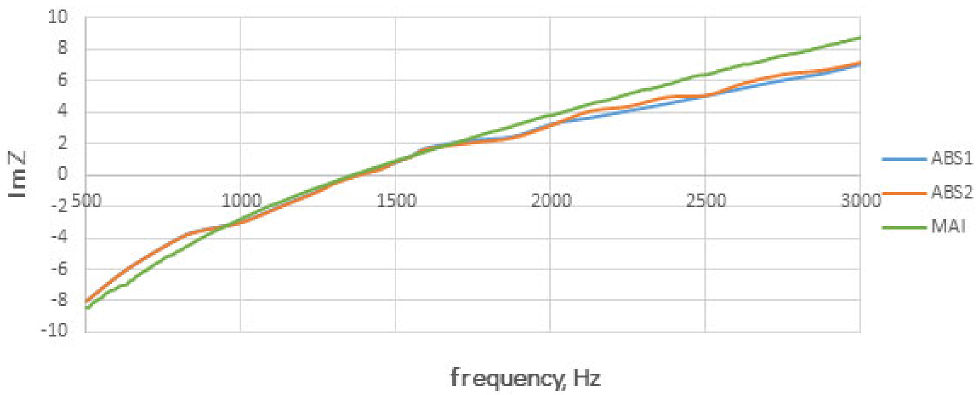


c) sound absorption coefficient (α)

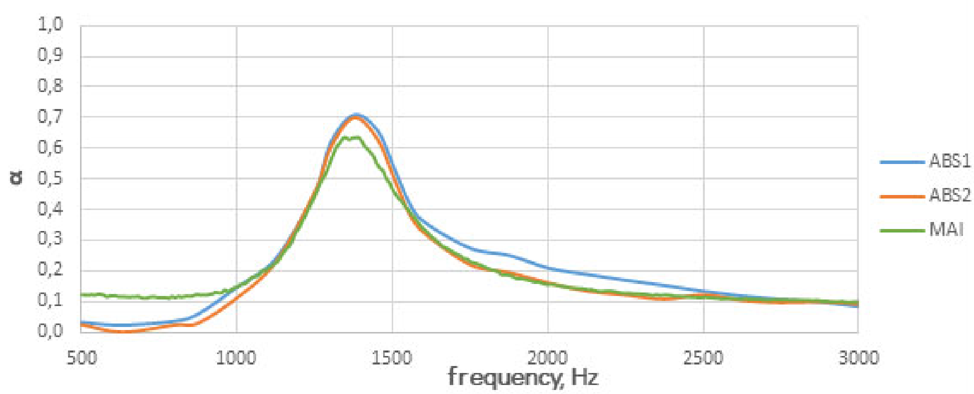
Fig. 6. Acoustic characteristics of sample A1 (diameter of the hole 3 mm): a) real part of the impedance (ReZ); b) imaginary part of the impedance (ImZ); c) sound absorption coefficient (α).



a) real part of the impedance (ReZ)

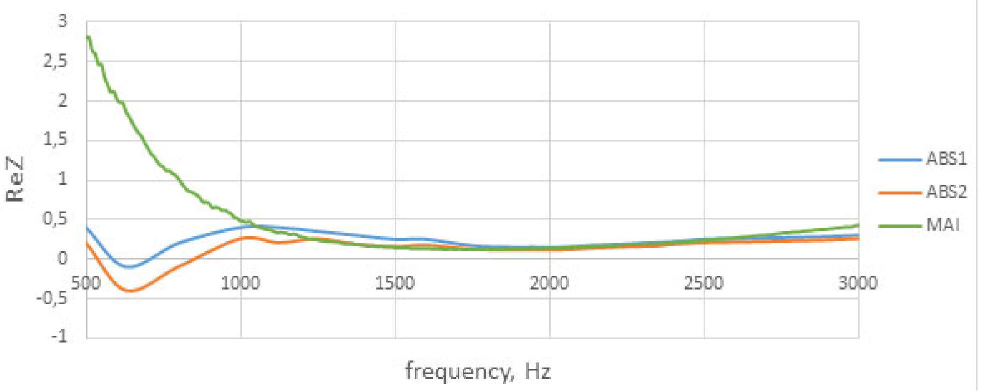


b) imaginary part of the impedance (ImZ)

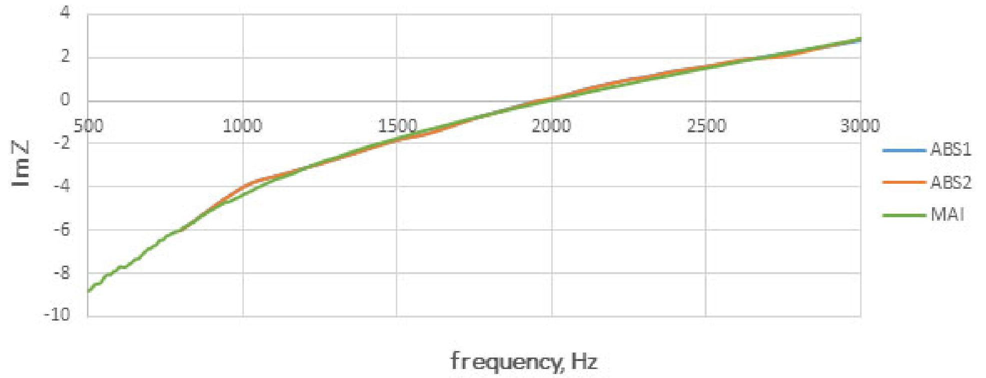


c) sound absorption coefficient (α)

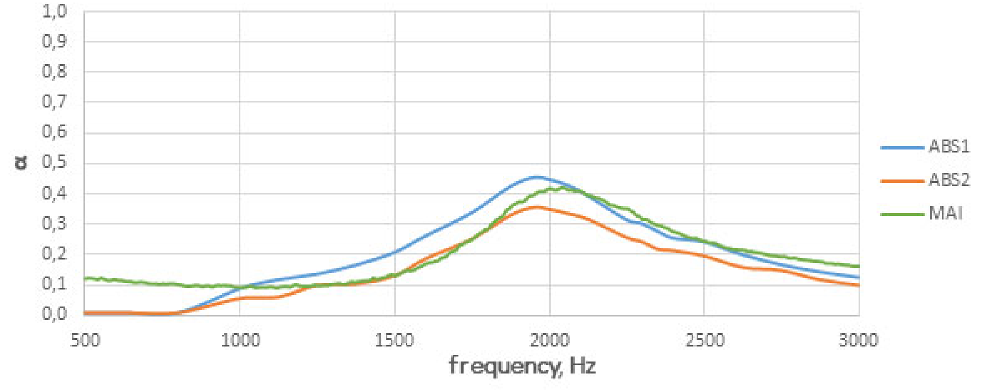
Fig. 7. Acoustic characteristics of sample A2 (diameter of the hole 5 mm): a) real part of the impedance (ReZ); b) imaginary part of the impedance (ImZ); c) sound absorption coefficient (α).



a) real part of the impedance (ReZ)



b) imaginary part of the impedance (ImZ)



c) sound absorption coefficient (α)

Fig. 8. Acoustic characteristics of sample A3 (diameter of the hole 8 mm): a) real part of the impedance (ReZ); b) imaginary part of the impedance (ImZ); c) sound absorption coefficient (α).

The acoustic characteristics of an "EKOHOR" sound-absorbing material of various heights - 50, 80 and 100 mm (Figure 9) were compared based on the results of tests on the MAI “interferometer” and the manufacturer's data published on the website in the public domain.

Table 1 shows the results of a comparative assessment of the sound absorption coefficient (α) according to ISO 10534-2, which is publicly available on the manufacturer's website (https://echocor.ru/urovni-zvukopogloshcheniya/) with the results obtained during measuring on the MAI “interferometer”. The average deviation of the sound absorption coefficient in the third–octave frequency bands is 3% for samples with a height of 50 mm, 2% for samples with a height of 80 mm and 100 mm. It is worth noting that deviations in the sound absorption coefficient can be caused by changes in the density of the material in the samples, since this is a material based on foamed melamine, its density varies between 8-11 kg/m^3.

Fig. 9. Samples of "EKOHOR" sound-absorbing material of various heights of 50, 80 and 100 mm with a diameter of 30 mm for research at the MAI “interferometer” installation.

Table 1. Comparison of the results of the determination of the sound absorption coefficient (α) according to ISO 10534-2, presented in the public domain, with the measurement results at the MAI installation for sound-absorbing "EKOHOR" material of various heights.

SAS	**height 50 mm**		**height 80 mm**		**height 100 mm**	
f, Hz	[34]	MAI	[34]	MAI	[34]	MAI
500	0.54	0.55	0.88	0.83	0.97	0.90
630	0.66	0.67	0.94	0.91	0.98	0.94
800	0.78	0.78	0.97	0.96	0.97	0.95
1000	0.87	0.85	0.97	0.98	0.96	0.95
1250	0.93	0.81	0.97	0.98	0.96	0.95
1600	0.97	0.98	0.95	0.98	0.95	0.98
2000	0.96	0.99	0.94	0.92	0.96	0.96
2500	0.95	0.96	0.95	0.99	0.98	0.98
3150	0.92	0.94	0.98	0.99	0.98	0.98
4000	0.94	0.96	0.99	0.98	0.96	0.99
5000	0.97	1.00	0.99	0.99	0.99	0.99

4 Conclusion

As part of this work, an “interferometer” installation with a normal incidence of sound waves was created at MAI to study the acoustic properties of sound-absorbing materials and structures. The equipment and main characteristics of the MAI interferometer type installation, such as the frequency range of 300-6600 Hz, the maximum amplitude of the sound pressure of 160 dB in the installation channel, the geometric characteristics of the waveguide, etc. are not inferior to the installations of Bruel&Kjaer, BSWA, Mecanum, Acoustic Awareness, Müller-BBM Industry Solutions GmbH, as well as those used in the Russian Federation.

The design of the "interferometer" proposed by the authors, in comparison with known analogues, has better operational manufacturability, reduces the time for installation and removal of the studied samples, and reduces the dispersion of the acoustic characteristics obtained (impedance, sound absorption coefficient) of the samples.

A comparative analysis of the acoustic properties obtained by measuring samples of SAS and materials in the laboratory of “Vibroacoustics and acoustic design of aviation technology” of MAI and the data presented in the public domain showed that at the initial stage of commissioning the “interferometer” installation in MAI, good convergence of the acoustic characteristics of the samples was achieved. The verification process of the MAI “interferometer” installation with a normal sound wave incidence will continue.

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