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The design of an impedance tube and testing of sound absorption coefficient of selected materials

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Abstract. The paper describes a design, building and testing a low-cost impedance tube for measuring the acoustic parameters of small testing samples. The measurement of sound absorption coefficient is based on transfer function and the two microphone method in accordance with ISO 10534-2 and ASTM E 1050 standards. With small configuration updates and after installation of additional microphones on measuring apparatus testing of complex acoustic material properties can be performed. The impedance tube has been used also as a teaching tool.

1. Introduction

The acoustic properties of materials such as sound absorption coefficient, reflection factor or transient loss (sound reduction) are determined experimentally. Several methods are in the role of determining the acoustic properties of materials on small samples. Procedure to ensure the measurement accuracy and repeatability of acoustic properties of materials, processing of measured results is prescribed by normative regulations in ISO 10534-1 (standing wave ratio method), ISO 10534-2, ASTM E 1050 (two microphone transfer function method for measurement of acoustic factor, sound absorption coefficient, specific acoustic impedance ratio, and specific acoustic admittance), and ASTM E 2611 (transient loss measurement) [1-3].

For testing the acoustic properties of materials according to the mentioned standards different impedance tubes were used. Most widely used is the set of Brüel&Kjær impedance tubes Type 4206 [4], which are something like industry standard in testing the acoustic material properties. Other commercially available tubes offer e.g. companies [5-8]. However, these commercially available tubes are expensive. Therefore, like other authors especially from universities, we went to develop a noncommercial tube. The design of low-cost impedance tubes suitable in the teaching process are presented in [9-10]. More complex solution is presented in works [11-13].

The design of a tube was carried out in accordance with ISO and ASTM Standards and also with respect to conclusions and recommendations resulting from the papers [14-15]. The procedure for measuring and processing of the results is described in [16-17].

2. Design of an impedance tube for the transfer function method

The impedance tube needs to be straight, with a smooth, nonporous inner wall. The material of the tube has to be strong and the thickness of the wall must prevent the vibrations within operating frequency range of the tube. The recommended value of the wall thickness is equal to 5 % of inner tube diameter. The design of the tube has to ensure that the upper limiting frequency of interest f_u is lower than the lowest cut-off frequency of the tube. That condition allows to arise only plane propagating waves inside the tube. This state is expressed by [3] as:

$$d < K\frac{c}{f_u} \tag{1}$$

where *fu* is the upper working frequency of the tube, and *c* is the speed of sound in the air at actual temperature. For a circular cross-section of the tube, *d* [m] is its inner diameter. For the constant ASTM E 1050 [3] uses $K = 0.586$, whereas ISO 10534-2 [2] considers $K = 0.58$. For a rectangular cross-section, *d* is its largest section dimension and both standards use $K = 0.5$. The second condition to develop the plane wave in the tube is its sufficient length *l*. Minimum distance between sound source and first microphone (microphone A in Figure 1) must by equal to the inner diameter of the tube *d*, but it is recommended to meet the condition:

$$l - s - x_2 > 3d \tag{2}$$

Equations (1) and (2) are used to define the main dimensions of the impedance tube to avoid non-plane propagating waves, as required by measurements.

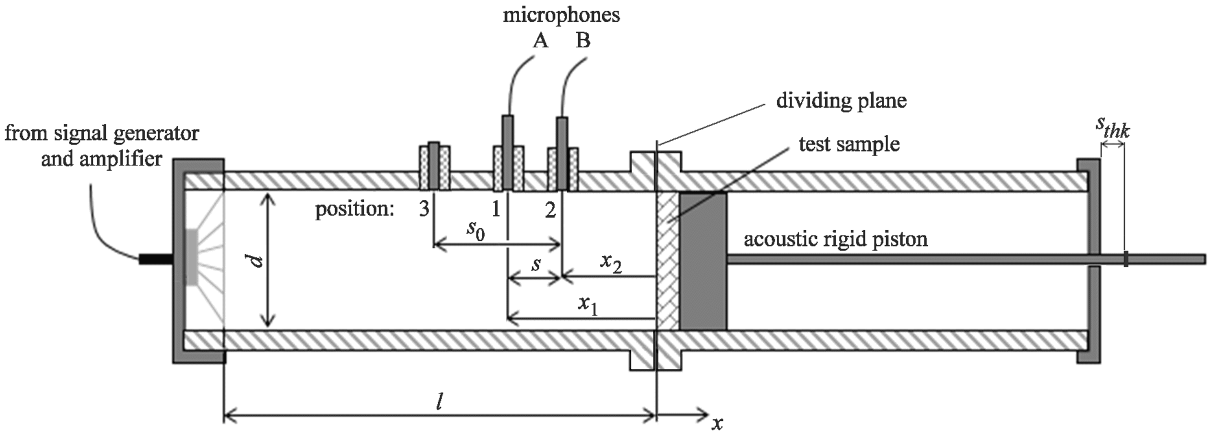


Figure 1. Design parameters of the impedance tube.

The both standards (ISO and ASTM) recommend using microphones of the same type designed for free sound field. Microphones membrane diameter d_{mic} must be much smaller (less than 20%) than the distance *s* between them, for a circular cross-section impedance tube to reduce the influence of their acoustic centers. Typically, 1/4 or 1/2 inch diameter size microphones are used for measurement. At the time of the tube design, there were the microphones B&K Type 4189-A-021 (1/2 inch microphone for open-field with pre-amplifier Type 2671, frequency range 20 Hz to 20 kHz, pre-polarized) available for measurement at our workplace. Spacing *s* between the measurement microphones in positions 1 and 2 governs the relations:

$$\begin{aligned} & d_{mic} < 0{,}2s \\ & f_u\, s < 0{,}45c \qquad \text{(ISO 10534-2)} \\ & f_u\, s < 0{,}40c \qquad \text{(ASTM E 1050).} \end{aligned} \tag{3}$$

Position of the third microphone with distance s_0 between point 2 and 3 (in Figure 1) depends on the lower limiting frequency f_l of the tube

$$s_0 > 0.05\frac{c}{f_l} \tag{4}$$

The upper f_u and lower f_l limit of the tube working frequency range can by calculated using relations:

$$f_u < K\frac{c}{d} \quad \text{and}$$

$$f_l > 0.01\frac{c}{s} \text{ (ASTM E 1050)} \quad \text{or} \quad f_l > 0.05\frac{c}{s} \text{ (ISO 10534-2).}$$

The spacing x_2 between the test sample and the closest microphone (microphone B in Figure 1) must prevent the proximity distortions in the acoustic field [14]:

- non-structured layer $x_2 > d/2$
- semi-lateral structured layer $x_2 > d$ (5)
- strongly asymetrical layer $x_2 > 2d$

Generally, the tube cross-section (diameter) must decrease if the maximum frequency of interest f_u increases. The non-plane waves always arise at the vicinity of the sound source and the test specimen surface. Therefore, the microphones cannot be placed close to the both tube ends. It is recommended to leave a distance of at least three tube diameters between the loudspeaker and its nearest microphone, and two tube diameters between the test specimen and the nearest microphone [2].

3. Transfer function method

The two-microphone impedance method is based on measuring the sound pressure in the impedance tube at two positions and calculation of the transfer function of acoustic pressure field between them. Figure 2 shows the apparatus for the measurement of acoustic properties of materials by a two-microphone method.

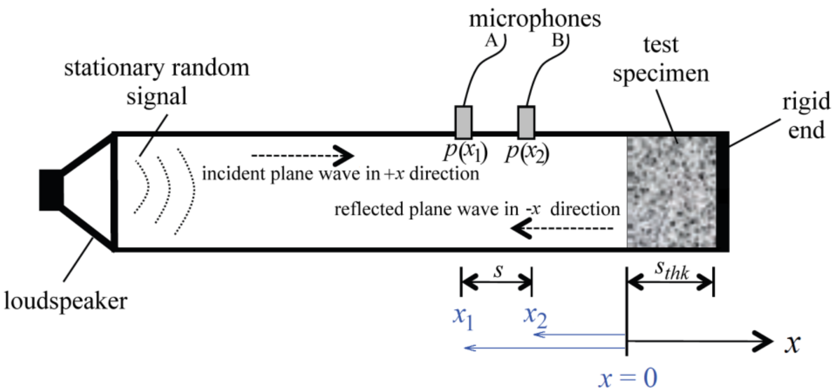


Figure 2. Scheme of two-microphone transfer function method.

The wave field in the tube is characterized by the acoustic pressure $p(x)$ of the incident wave $p_I(x)$ and the wave reflected from the sample $p_R(x)$. Total sound pressure $p(x)$ at any point in the tube is

$$p(x) = p_I(x) + p_R(x) = Ae^{-\mathrm{i}kx} + Be^{\mathrm{i}kx} \tag{6}$$

where A, B are amplitudes of the acoustic pressures of the incident and reflected wave and $\mathrm{i} = \sqrt{-1}$. Let $P(x,\omega)$ is the Fourier transform of $p(x)$ for the given location x, where ω is the angular frequency. The transfer function H_{12} of acoustic pressure field between positions 1 and 2 is defined by the complex ratio:

$$H_{12} = \frac{P(x_2,\omega)}{P(x_1,\omega)} = \frac{e^{-\mathrm{i}kx_2} + r\,e^{\mathrm{i}kx_2}}{e^{-\mathrm{i}kx_1} + r\,e^{\mathrm{i}kx_1}} \tag{7}$$

where r is the reflection factor of tested material and k is the wave number.

The reflection factor r is a complex number due to consideration of a phase shift of the waves. The estimation of the complex acoustic transfer function H_{12} can be carried out in three ways as follows:

$$H_{12} = \frac{S_{12}}{S_{11}}$$ can be used generally,

$$H_{12} = \frac{S_{22}}{S_{21}}$$ recommended for cases where noise is at input e.g. if white noise is used to activate the acoustic waves in the tube, standard ASTM recommends to use this equation to determine the transfer function, (8)

$$H_{12} = \left(\frac{S_{12}}{S_{11}}\frac{S_{22}}{S_{21}}\right)^{1/2}$$ recommended for cases involving noise is at input and output,

where S_{12} is the cross-spectrum of the signal from microphones A and B, S_{11} is the autospectrum of the signal from microphone A, S_{22} is the autospectrum of the signal from microphone B, and S_{21} is the cross power spectral density of the signal from microphones B and A.

When using the two microphone technique, procedure of repeated measurements with interchanged channels for correcting the measured transfer function data must be used. When the test specimen is placed in the tube, two transfer functions H_{12}^{I} and H_{12}^{II} are estimated. For the first time, the microphones A, B are in positions 1, 2 (standard configuration I), as shown in Figure 1, and the transfer function H_{12}^{I} is determined. For the second measurement positions of microphones are switched on. Microphone A is in the position 2 and microphone B is in the position 1 (interchanged configuration II). Corrected transfer function H_{12} is computed using the equation:

$$H_{12} = \left(H_{12}^{\mathrm{I}}\, H_{12}^{\mathrm{II}}\right)^{1/2} = H_r + jH_i \tag{9}$$

where H_r is the real component and H_i is an imaginary part of the transfer function H_{12}.
The acoustic reflection factor r of the test specimen is from equation (7) defined as:

$$r = r(\omega) = \frac{H_{12} - e^{-jks}}{e^{jks} - H_{12}} e^{2jk(s+x_2)} = r_r + jr_i \tag{10}$$

The sound absorption coefficient α is the dimensionless quantity with the values in the range of $\langle 0, 1\rangle$, given as [2]:

$$\alpha = \alpha(\omega) = 1 - |r|^2 = 1 - r_r^2 - r_i^2 \tag{11}$$

Reflection factor r and sound absorption coefficient α vary with the frequency and angle of sound wave incidence. In the case, that the material perfectly reflects all incident sound waves from the surface, the sound absorption coefficient is $\alpha = 0$. In the case that the material absorbs all incident energy, the sound absorption coefficient is $\alpha = 1$. Therefore, the materials with porous or fibrous structure are recommended for the absorption of sound.

Specific acoustic impedance ratio Z is calculated from the equation:

$$Z = Z(\omega) = \rho c \frac{1+r}{1-r} \tag{12}$$

where ρ is the density of the air at actual temperature and the product (ρc) represents the characteristic impedance.

4. Building the impedance tube

The designed impedance tube is made of the thick walled HDPE pipe with the circular cross-section uniform along the length. The main design parameters of the tube are summarized in Table 1.

Table 1. Parameters of the impedance tube.

Parameter	Value
inner diameter of the tube d	0.088 m
tube wall thickness t	0.010 m
tube length l	0.758 m
distance x_2 of nearest microphone and sample[a]	0.100 m
distance s between microphone positions 2 and 1	0.065 m
distance s_0 between microphone positions 2 and 3	0.150 m
lower limiting frequency f_l of the tube	200 Hz
upper limiting frequency f_u of the tube	3000 Hz

[a] *Distance can be changed by insertion of separate test sample holder*

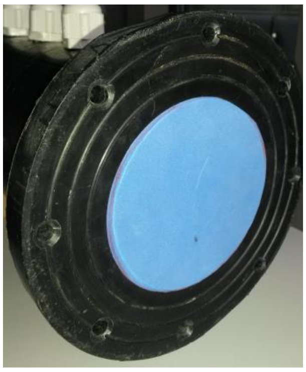
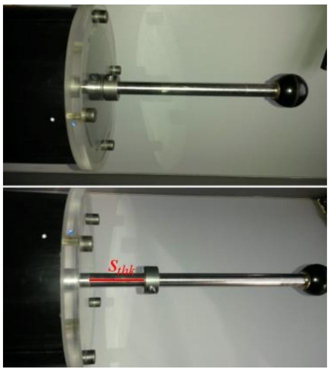
The air tightness of the tube under microphone holders was ensured by gluing. The rubber seal arround the microphone body is also used to determine the correct insertion depth into the holder (Figure 3a). Microphones are flush mounted in their positions (Figure 3b).

a) 

b) 

Figure 3. Design of mic holders (a) and details of the correct microphone installation (b).

Both parts of the impedance tube are joined together by screws. The second opposite tube has the same dimension parameters as the measurement tube. It contains the rigid piston and test samples inserted into this tube (Figure 4a). From the displacement of the piston, the sample thickness s_{thk} can be checked after insertion and/or depth of the air cavity in the back of the test sample (Figure 4b).

a) 
b) 

no sample inserted in the tube

inserted sample in the tube with thickness s_{thk}

Figure 4. Test sample installation.

The sound source is a loudspeaker mounted in a sealed box combined with a signal amplifier based on audio chip TDA2030 in the recommended circuit connection. The final design of the impedance tube prototype shows Figure 5. In the next work piezo-exciter as the sound source will be tested.

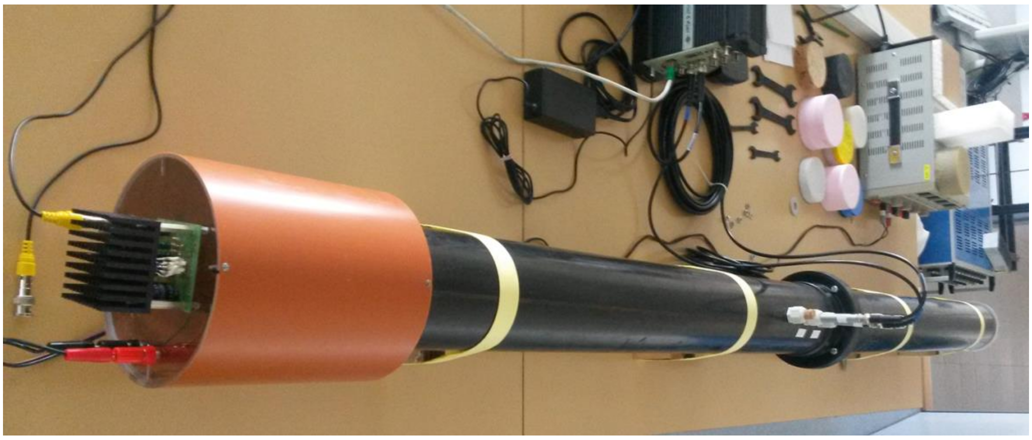


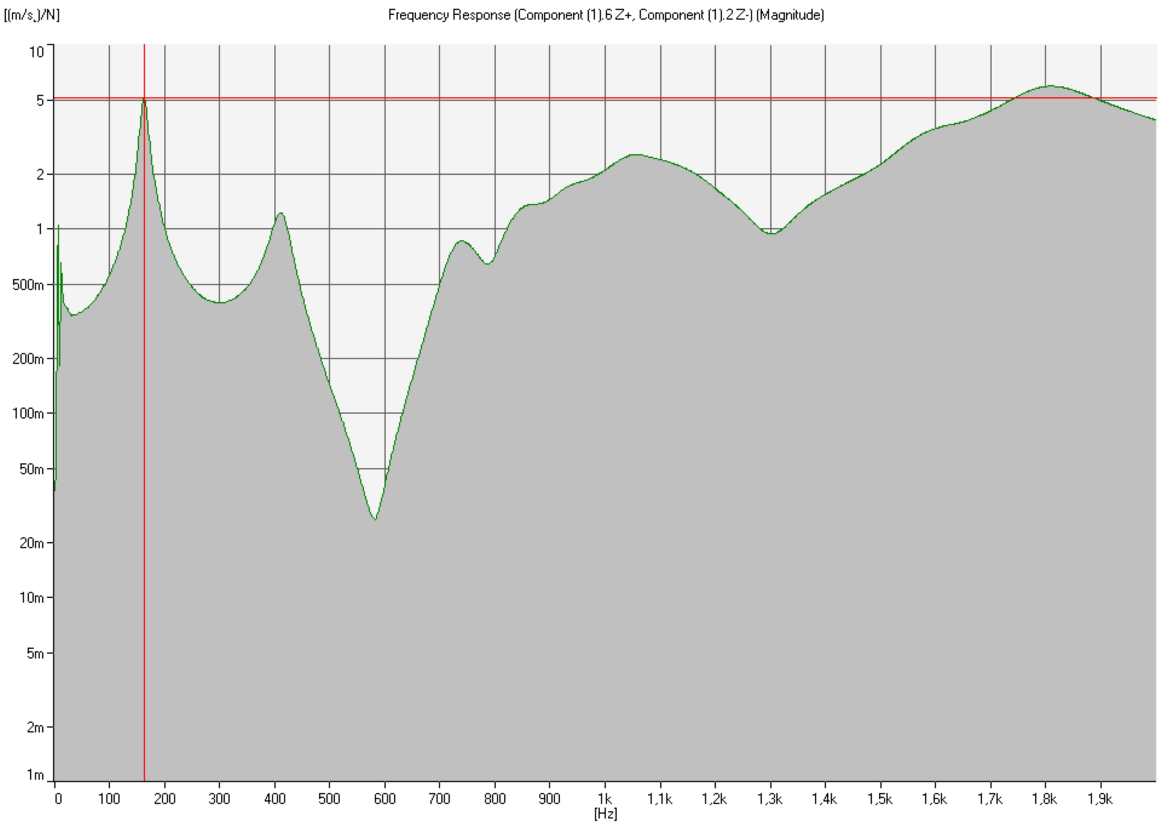
Figure 5. Prototype of the complete impedance tube.

5. Determination of natural frequencies of the impedance tube

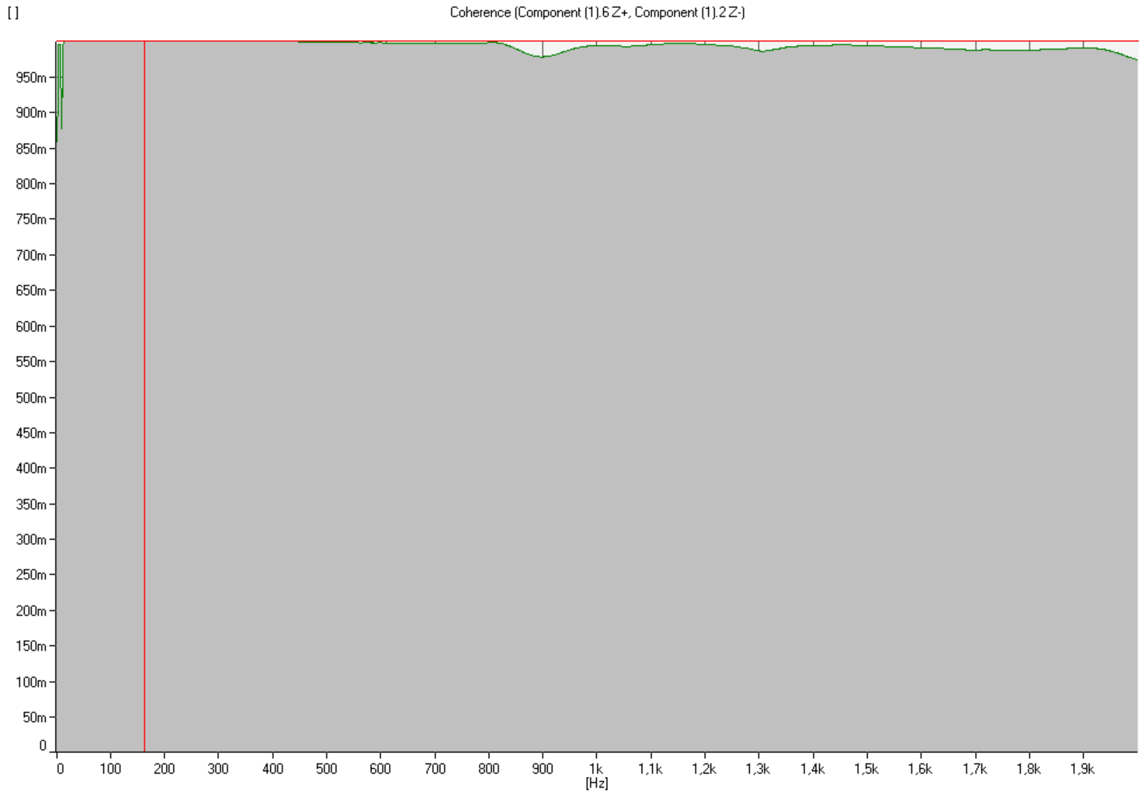
The general way to identify the modal parameters of the structure is fitting a linear model by the Frequency Response Function (FRF), a function related to the excitation frequency spectrum $F(f)$ to the response frequency spectrum $X(f)$

$$X(f) = H(f)\,F(f) \tag{13}$$

Instrumentation used for the determination of natural frequencies of made impedance tube: hardware unit Brüel & Kjær FFT Analyzer Type 3560-B-120, four accelerometers Brüel & Kjær Type 4508-B, and modal hammer Brüel & Kjær Type 8206-001 with plastic tip. The accelerometers were installed at the tube using beeswax.



a)



b)

Figure 6. Determination of modal parameters of the impedance tube (a) FRF and (b) the coherence function.

In Figure 6a, magnitude of frequency response function obtained by accelerometer placed near the microphone holder at position 2 is presented. Coherence function in Figure 6b indicates degree of linear relationship between the input and response signal at the working frequency range of the tube. From the experimental results of the modal analysis it followed that the 1st natural frequency was 164 Hz, under the range of interest for acoustic measurement, but the 2nd natural frequency 411 Hz with lower amplitude was near theoretical lowest limit frequency of the tube.

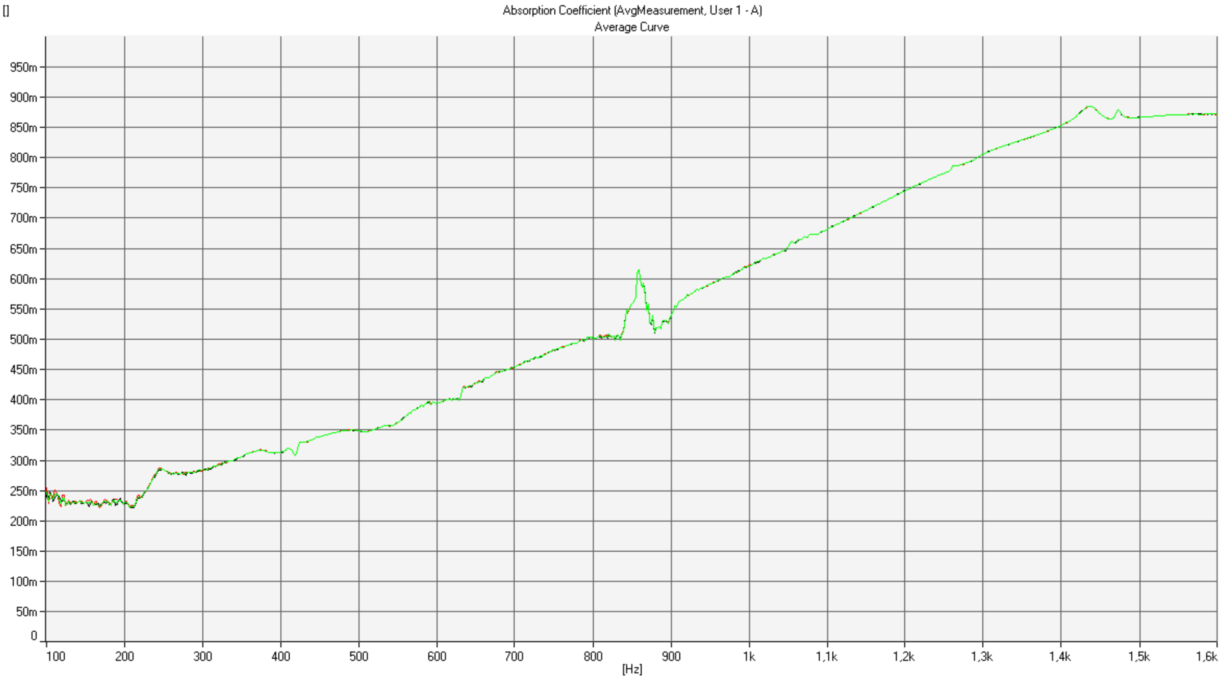
6. Measurement of the sample acoustic properties

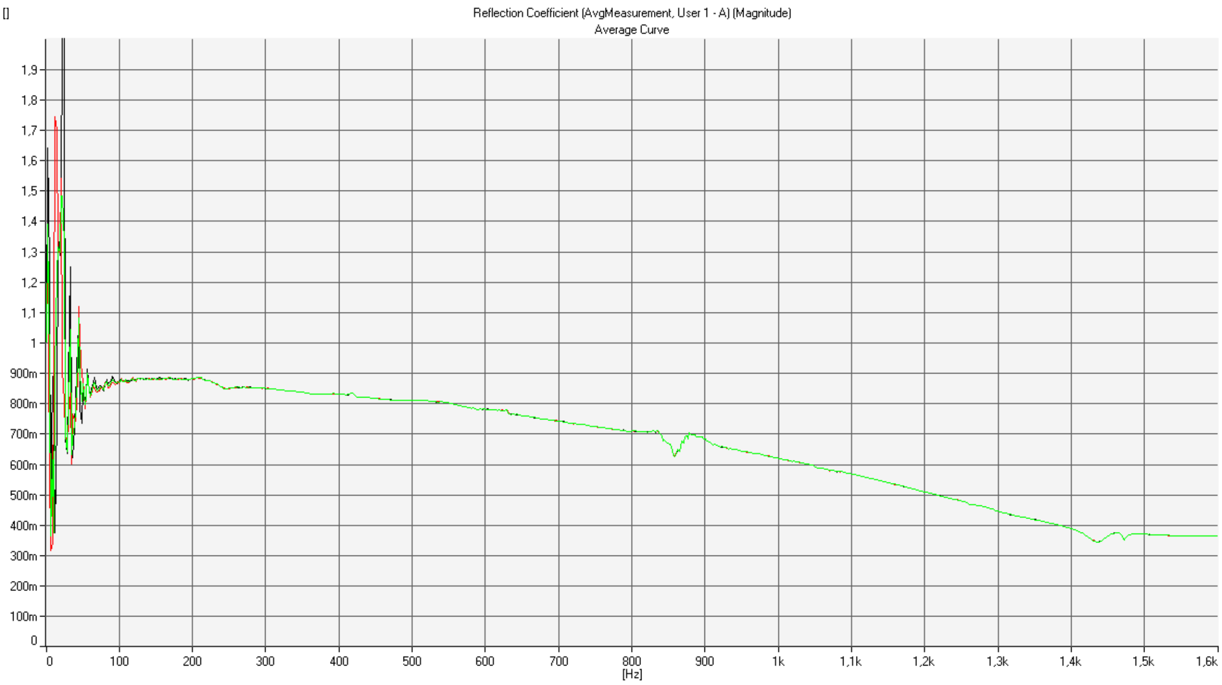
The following equipment was used for the measurement based on the transfer function method: hardware unit Brüel & Kjær FFT Analyzer Type 3560-B-120, two microphones Brüel & Kjær Type 4189-A-021, built impedance tube with a signal amplifier, software Brüel & Kjær Pulse Labshop and as the source of white noise PC audio card was used. Acoustic material properties of foam were determined in the frequency range from 200 Hz to 1600 Hz. The sample was cut using a laser graving and cutting machine. The parameters of the test sample are summarized in Table 2.

Table 2. Parameters of the test specimen.

Parameter	Value
diameter d of the sample	0.088 m
thickness s_{thk} of the sample	0.044 m
material	foam
density ρ	28.25 kg.m^{-3}

All the measured data were processed by Pulse LabShop software. Figure 7 shows the results of acoustic material properties measurement during the test of impedance tube. Variation of the sound absorption coefficient (Figure 7a), the reflection factor (Figure 7b), and real part of the specific acoustic impedance ratio (Figure 7c) of the foam test samples are presented in following graphs. The sound absorption coefficient curve measured for foam of 44 mm thickness has similar tendency as results presented in [9] for the foam with thickness 40 mm. The constructed tube shows certain discontinuity of sound absorption coefficient and reflection factor around the frequency 850 Hz.





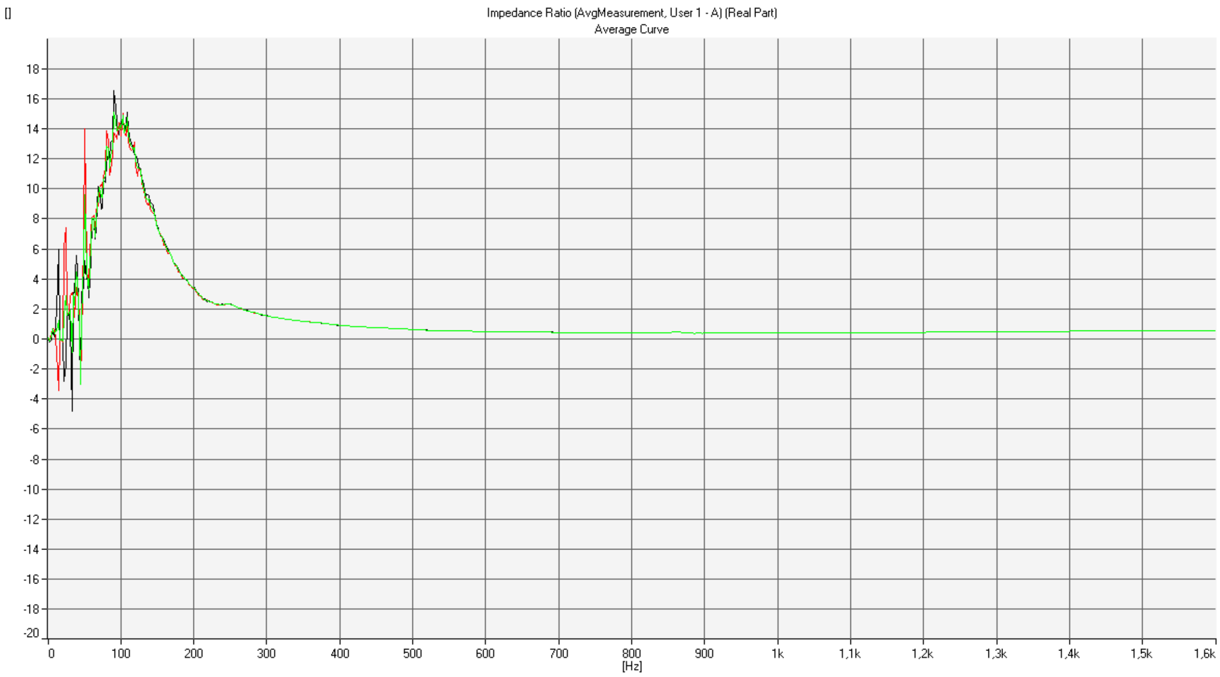


Figure 7. Frequency dependence of sound absorption coefficient, reflection factor and acoustic impedance ratio (real part) of tested foam material.

7. Summary

The design of the low-cost impedance tube is presented in this article. The prototype of the tube can be used for testing of acoustic properties of material in accordance with the mentioned ISO and ASTM Standards. The tested sample demonstrated approximately a linear rise of the sound absorption coefficient with the frequency in the range of interest. The reflection factor decreased its value in dependence on the frequency. In our future research, we plan to compare the acoustic properties of different materials measured by our impedance tube with the results obtained by a certified authority.
The measurements performed by new impedance tube so far show similar results to those available in the literature for equivalent materials. It can be concluded that the transfer function for measuring the normal incidence sound absorption coefficient is more effective as the method of standing wave ratio and application of discrete frequencies. It is expected that the certain drops in curves of acoustic coefficients can be improved using a more rigid tube, smaller microphones (1/4"), second tube with smaller diameter and different broadband excitation signals.

Acknowledgement

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