FACTA UNIVERSITATIS
Series: **Working and Living Environmental Protection** Vol. 21, Nº 1, 2024, pp. 1 - 17
https://doi.org/10.22190/FUWLEP240314001M

Original Scientific Paper

SOUND ABSORPTION COEFFICIENT MEASUREMENT METHODS IN REVERBERATION ROOM AND IMPEDANCE TUBE

UDC 535.341.534.843.2

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Abstract. *Sound absorption materials are very often used for space design in order to reduce the noise level and adjust the acoustic characteristics of the space depending on its purpose. Therefore, knowledge of the acoustic quantities that characterize sound absorption materials is of crucial importance. The most commonly used acoustic quantity is the sound absorption coefficient, which can be determined using standardized methods and methods used only for research purposes. This paper will provide an overview of the most commonly used standardized methods for determining the sound absorption coefficient: the reverberation room method and the impedance tube method. Since the impedance tube method, which provides the normal incidence sound absorption coefficient, is more suitable when developing new absorption materials, and in practical applications, it is desirable to know the random incidence sound absorption coefficient, this paper discusses approaches for predicting the random incidence sound absorption coefficient based on the acoustic parameters of the sound absorption materials measured in an impedance tube.*

Key words: *normal incidence sound absorption coefficient, random incidence sound absorption coefficient, reverberation room method, incidence tube method*.

Received March 14, 2024 / Accepted April 9, 2024
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1. INTRODUCTION

There are many unwanted noise sources in our working and living environment that create an undesirable environment and have harmful effects on human health. Noise sources in both the working and the living environment are very diverse in terms of their physical forms, mechanisms, and characteristics of noise generation, so emitted noise in the time and frequency domain can be steady, fluctuating, intermittent, impulse, wideband, narrowband, tonal noise, etc.

Noise sources, acoustically defined by their sound power (or the sound pressure emission) and the radiation directivity, emit sound into the environment in which they are located. The sound heard is a combination of direct sound emitted by the sources and indirect reflections from adjacent surfaces and objects. Acoustic noise pollution resulting from the operation of these noise sources can be reduced by lowering the radiation of the noise source itself, by reflecting the sound in different directions, by dispersing it or by absorbing the sound energy. Sometimes it is impossible to reduce the radiation of the noise source itself, so in many cases, sound absorption materials are used to mitigate the acoustic pollution. Sound absorption materials are widely employed to solve noise problems: inside machine enclosures, on the side of barriers facing the road, inside ventilation ducts and pipelines, for acoustic treatment of rooms, within hearing protection cups, etc. Considering that the emitted noise can have different characters in the time and frequency domain, there are no universal sound absorption materials that would be used for all types of emitted noise. That is why knowledge of their acoustic characteristics is important for the application of sound absorption materials.

Sound striking a surface of sound absorption materials can be transmitted, absorbed or reflected. The amount of transmitted, absorbed and reflected energy depends on the acoustic properties of the sound absorption materials. The effect of the sound absorption material on the propagation of a sound wave can be characterized by four interrelated acoustic quantities: surface impedance, surface admittance, sound reflection coefficient and sound absorption coefficient [1]. Knowledge of these four acoustic quantities is fundamental to calculating noise reduction when applying sound absorption materials. In addition, the well-known Delaney and Beazley empirical model [1, 2] requires knowledge of the flow resistance and porosity of the acoustical material.

Over the years, sound absorption materials have constantly evolved and improved. New materials have become safer, lighter and technologically optimized. Furthermore, ecological concepts, sustainable development and the use of recycled and green building materials will soon play an important role in the application of sound absorption materials. These new directions encourage the development of new materials and/or the improvement of existing ones. Also, the main goal of the project [3] is to develop an advanced environmentally friendly technology for producing new biodegradable composite materials with improved sound insulating and sound absorbing properties. An increase in the insulating and absorbing ability of composites in the audio range will be achieved by using viscoelastic polymer components modified with nanosized carbon and silicate particles as the matrix phase [3].

Although there are well-known theoretical models for characterizing sound absorption materials used during the development of new materials [1], many methods have been developed over the years to measure acoustic quantities that characterize the sound absorption materials. Some of these methods are standardized (impedance tube and reverberation room method) and some are only used for research purposes. A review of methods for measuring the sound absorption coefficient of sound absorption materials in a reverberation room and impedance tube will be presented in this paper. Also, the approaches used for establishing the relationship between the random incidence sound absorption coefficient and normal incidence sound absorption coefficient will be presented.

2. REVERBERATION ROOM METHOD

The reverberation room method is used for determining the random incidence sound absorption coefficient, a parameter that is most often used in space design to specify the absorption performance of materials. The reverberant room method is standardized in ISO 354 [4] and ASTM C423 [5]. There are differences between these standards in terms of required sample size and room volumes, differences in sample mounting, and calculation methods [6].

The principle applied in the mentioned standards is based on the determination of the equivalent sound absorption of reverberation room with and without a mounted test sample. ASTM C423 uses only the interrupted noise method for the sound pressure decay rate measurement, while ISO 354 on the other hand uses the interrupted noise method and integrated impulse response method for the reverberation time measurement.

To apply the reverberation room method, it is necessary to have a diffuse sound field in the room, where the sound level has minimal changes throughout the room. For this purpose, diffusers are often used and the shape of the reverberation room shall be such that the following condition is fulfilled [4]:

$$l_{max} < 1.9V^{1/3}, \qquad (1)$$

where

- l_{max} is the length of the longest straight line which fits within the boundary of the room, in [m];
- V is the volume of the room, in [m^3].

Very often it can be expected that the sound field in the room is not completely diffused, so it is recommended to use multiple source and receiver positions and to average the results to reduce the effect of non-diffuseness.

Based on the measured sound pressure decay rate and reverberation time, the equivalent sound absorption area (in square meters) of the reverberation room for the empty reverberation room ($A_{ASTM,0}$, $A_{ISO,0}$) and reverberation room with a sample ($A_{ASTM,1}$, $A_{ISO,1}$) is determined using the following equations [7]:

$$A_{ASTM} = 0.921\frac{Vd}{c}, \qquad (2)$$

$$A_{ISO} = \frac{55.3V}{cT_R} - 4Vm, \qquad (3)$$

where

- c is the speed of sound, in [m/s];
- d is the sound pressure decay rate, in [dB/s];
- T_R is the reverberation time, in [s];
- m is the power attenuation coefficient calculated according to ISO 9613-1 [8], in [m^{-1}].

The random incidence (or diffuse field) sound absorption coefficient of the sample can be calculated as:

$$\alpha_r = \frac{A_1 - A_0}{S} + \frac{A_1}{S_0}\,, \tag{4}$$

where

S is the area of the sample, in [m^2];

S_0 is the area of the reverberation room boundary surfaces, in [m^2].

In ISO 354 and in reference [2], the second term in equation (4) is omitted, because the term [$S_0 - S$] is approximated to S_0, which simplifies the end formulation for the absorption coefficient of the sample [4].

In addition to the fact that the reverberation room method gives the random incidence sound absorption coefficient, most often used, this method also has certain disadvantages:

- the other acoustic characteristics of the sound absorption material, except the sound absorption coefficient, cannot be determined;
- large and expensive facilities are required;
- large samples are required which are not always available, especially in the developing material phase;
- position and size of the sample can influence the results [9];
- sound absorption coefficient values are often overestimated and higher than 1 (Fig.1), because of edge diffraction, non-diffuseness, and/or Sabine formulation [10];
- significant differences in results may occur for different reverberation rooms (Fig.1), also see [11].

The mean sound absorption coefficient for 13 different laboratories is shown for each sample in Fig.1, along with error bars indicating the 95% confidence limit. The left graph is for a 100 mm mineral wool absorber in a wooden casing covered with nonwoven fleece and the right is for a 25-mm-thick foam absorber [1].

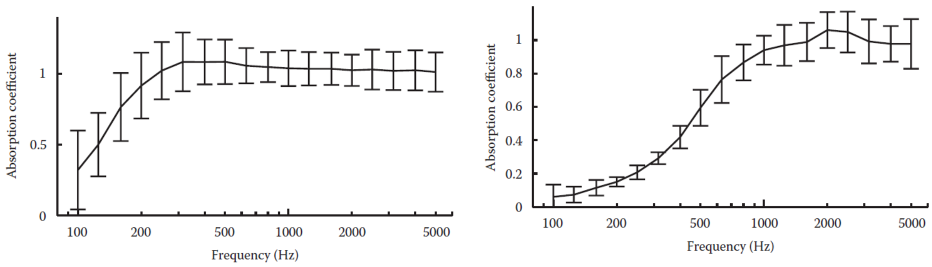


Fig. 1 Comparison of sound absorption coefficients for two different samples [1]

3. Impedance (Kundt`s) Tube Method

The impedance tube method, very often called a Kundt`s tube method, enables both the normal incidence sound absorption coefficient and surface impedance measurement. The measurement is carried out under well-defined and controlled conditions and is very often used in developing new sound absorption materials and validation of prediction methods. The advantage of this method is that it requires only small samples and relatively simple instrumentation that can be placed in a normal room. The time and costs of testing are far less compared to the reverberation room method. The problem in applying this method arises when small samples are not representative of the behavior of large samples, so it is most often used with porous absorbers.

There are different types of measuring the acoustic properties of materials using an impedance tube:

- Standing wave ratio method with one microphone
- Transfer function method with two/three microphones
- Transfer function matrix method with four microphones
- Transfer function method with two microflows
- P-U method.

3.1. Standing wave method with one microphone

ISO 10534-1 [12] and ASTM C-384-04 [13] specify a method for determination of the normal incidence sound absorption coefficient. In addition, it is possible to determine the normal incidence sound reflection coefficient, the surface impedance and surface admittance of the materials. The standing wave ratio method is the oldest and simplest direct method for measuring the acoustic properties of materials using the impedance tube with one microphone.

The material sample, whose acoustic characteristics are to be determined is mounted on one end of the impedance tube. At the other end, a loudspeaker is mounted to generate an incident plane sinusoidal sound wave. The generated sound wave is reflected from the material sample and the superposition of incident and reflected waves creates a standing wave in the impedance tube (Fig. 2). The standing wave created inside the tube contains a number of nodes and anti-nodes, with the minimum sound pressure level and maximum sound pressure level, respectively. The standing wave ratio, i.e. the ratio of the maximum sound pressure to the minimum sound pressure, is used to determine the normal incidence sound absorption coefficient. The maximum and minimum sound pressure is measured by moving the microphone (Fig. 3). The microphone is moved from the sample towards the loudspeaker, and the first sound pressure level minimum is detected, then the following maximum is detected. Normally the sound pressure level will first experience a maximum when moving the microphone from the sample towards the loudspeaker, as illustrated in Fig. 2, but the second maximum is used for determining the standing wave ratio [14]. This procedure is repeated for all frequencies of interest.

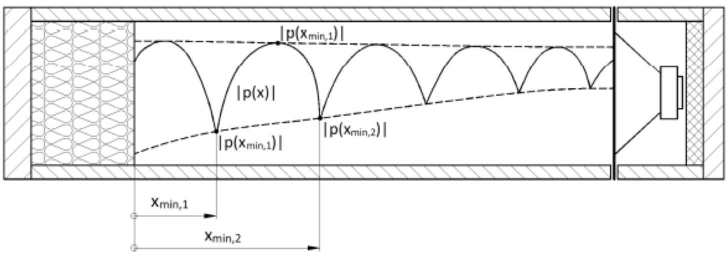


Fig. 2 Schematic view of the standing wave ratio method [2]

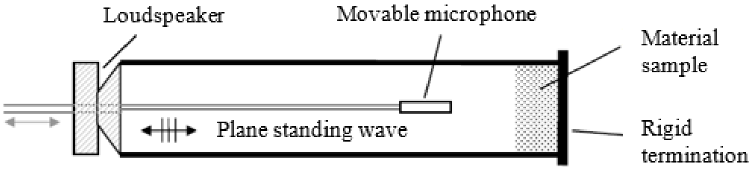


Fig. 3 Measurement setup for the standing wave ratio method with one microphone (adopted from [7])

If the difference between the maximum sound pressure level and the minimum sound pressure level is ΔL [dB], then the normal incidence sound absorption coefficient follows [12]:

$$\alpha_{\mathrm{n}} = \frac{4 \cdot 10^{\Delta L/20}}{(10^{\Delta L/20} + 1)} . \tag{5}$$

The results of the investigation of the sound absorption characteristics of single and multi-layered porous materials presented in the paper [15] show that the standing wave method is simpler but the transfer function method is a more accurate approach.

3.2. Transfer function method with two/three microphones

ISO 10534-2:2008 [16] describes the method for determining the normal incidence sound absorption coefficient of sound absorbers using the transfer function between two microphone locations. The American standard ASTM E1050-19:2019 [17] describes this procedure in an almost identical way to the mentioned ISO standard. The method uses an impedance tube with a sound source connected to one end and the test sample mounted at the other end (as in ISO 10534-1), with two microphone locations and a digital frequency analysis system (Fig. 4). It can also be applied for determining the acoustical surface impedance or surface admittance of sound absorbing materials. In this method, the

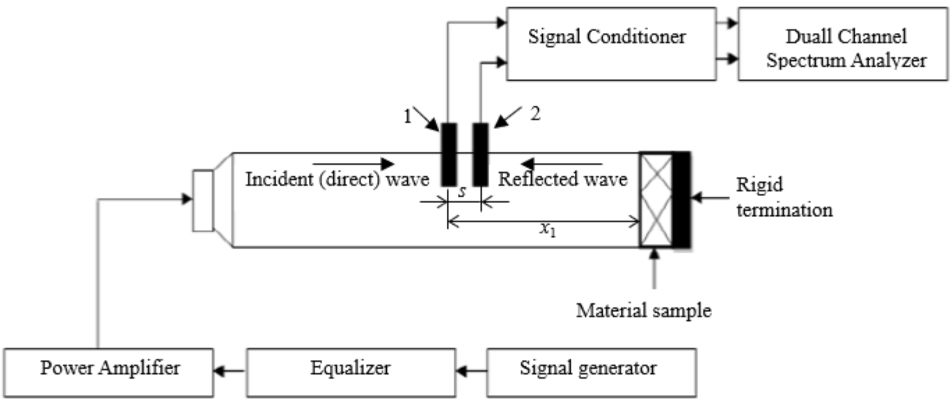


Fig. 4 Measurement setup for the transfer function method with two microphones (adopted from [18])

broadband excitation signal forms a standing plane wave in the tube, comprising two components: the direct waves moving from the sound source to the sample and the reflected waves moving from the sample surface to the other end of the tube where the sound source is located. Decomposition of the standing wave is achieved by simultaneously measuring the sound pressure at two spatially separated positions on the tube surface using two wall-mounted microphones and then calculating the complex acoustic transfer function, the normal incidence sound absorption coefficient and the impedance ratios of the acoustic material.

The complex sound pressure levels, $\underline{p}_1$ and $\underline{p}_2$, are measured at the microphone position 1 and 2, and the normal incidence sound absorption coefficient is determined as [16]:

$$\alpha_{\mathrm{n}} = 1 - |\underline{r}|^2 . \tag{6}$$

The complex normal incidence sound reflection coefficient, $\underline{r}$, is determined as:

$$\underline{r} = |\underline{r}| e^{j\phi_r} = \frac{\underline{H}_{12} - e^{-jks}}{e^{jks} - \underline{H}_{12}} e^{2jkx_1} . \tag{7}$$

where

x_1 is the distance between the material sample and the microphone position 1, in [m];

k is the wave number, $k = 2\pi f / c$ (f is the frequency, c is the speed of sound);

$\underline{H}_{12}$ is the transfer function between two microphone positions 1 and 2:

$$\underline{H}_{12} = \frac{\underline{p}_2}{\underline{p}_1} = \frac{\underline{S}_{12}}{\underline{S}_{11}} = \frac{\underline{S}_{22}}{\underline{S}_{21}} = \sqrt{\frac{\underline{S}_{12}}{\underline{S}_{11}} \cdot \frac{\underline{S}_{22}}{\underline{S}_{21}}} . \tag{8}$$

In eq. (8), $\underline{S}$ represents the auto/cross spectrum determined as the product of complex sound pressures at corresponding microphone positions, for example $\underline{S}_{12} = \underline{p}_2 \cdot \underline{p}_1^*$. The transfer function must be compensated for phase and amplitude mismatch of the microphones by the procedure described in [16, 17].

The slightly modified method is described in the paper [18]. The same measurement setup is used, but instead of the transfer function, the auto spectra of the incident and reflected waves are determined. The two microphones placed in two locations measure the auto spectrum S_{11} and S_{22} and the cross spectrum $\underline{S}_{12} = X_{12} + jY_{12}$. The auto spectrum of the incident and reflected waves, $\underline{S}_{\mathrm{AA}}$ and $\underline{S}_{\mathrm{BB}}$, are determined as [17]:

$$\begin{bmatrix} \underline{S}_{\mathrm{AA}} \\ \underline{S}_{\mathrm{BB}} \\ X_{\mathrm{AB}} \\ Y_{\mathrm{AB}} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 2\cos(2kx_1) & 2\sin(2kx_1) \\ 1 & 1 & 2\cos(2kx_2) & 2\sin(2kx_2) \\ \cos(kn) & \cos(kn) & 2\cos(km) & 2\sin(km) \\ -\sin(kn) & \sin(kn) & 0 & 0 \end{bmatrix}^T \cdot \begin{bmatrix} \underline{S}_{11} \\ \underline{S}_{22} \\ X_{12} \\ Y_{12} \end{bmatrix} , \tag{9}$$

where $\underline{S}_{\mathrm{AB}} = X_{\mathrm{AB}} + jY_{\mathrm{AB}}$ is the cross spectrum between the incident and reflected waves, $m = x_1 + x_2$ and $n = x_1 - x_2$. The distance x_1 and x_2 are illustrated in Fig. 5.

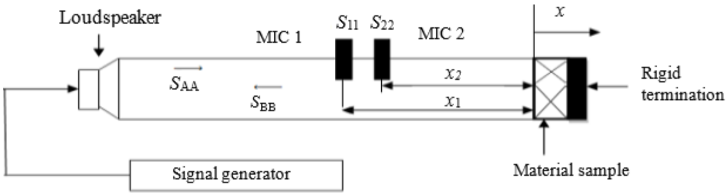


Fig. 5 Measurement setup for the transfer function method with two microphones (adopted from [18])

The normal incidence sound absorption coefficient is calculated from:

$$\alpha_n = 1 - \left| \frac{\underline{S}_{BB}}{\underline{S}_{AA}} \right|^2 , \tag{10}$$

where $\underline{S}_{AA} = X_{AA} + jY_{AA}$ and $\underline{S}_{BB} = X_{BB} + jY_{BB}$.

The two-microphone transfer function method can be enhanced to determine additional material characteristics by incorporating an extra microphone mounted flush with the inner wall of the rigid termination of the impedance tube. The characteristic impedance, wave number, equivalent bulk modulus and equivalent density of the material sample can be calculated based on the measurement results [19, 20]. An impedance tube configuration with three microphones is illustrated in Fig. 6.

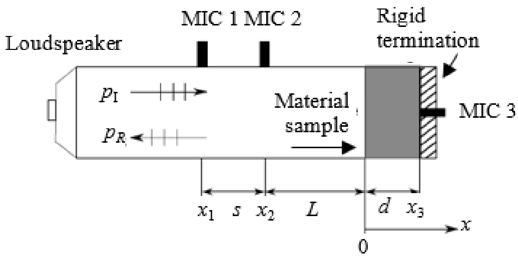


Fig. 6 Impedance tube configuration with three microphones (adopted from [21])

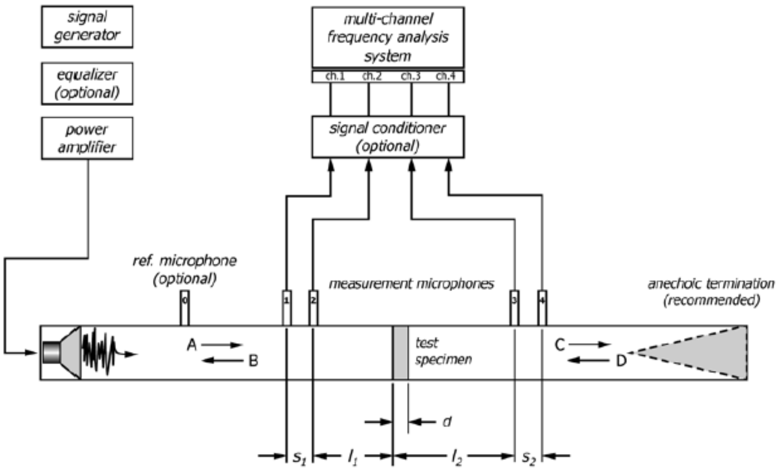
For testing the acoustic characteristics of the material, a standardized impedance tube described in ISO 10534-2:2008 and ASTM E1050-19:2019 is used [10, 22]. Due to the high cost of commercially available impedance tubes and the associated measurement software, the impedance tubes were designed and constructed using low-cost materials, but without reducing the accuracy and reliability of the measurement results [23, 24].

The investigation results obtained by applying the two-microphone transfer function method [25-27] indicate that this method can also be used to determine the absorption characteristics of the new composite materials [23].

3.3. Transfer function matrix method with four microphones

The standard test method for determining the acoustic properties of porous materials at normal incidence based on the transfer function matrix method described in the American standard ASTM E2611-19 [28] is primarily intended for determining normal incident sound transmission loss, but it can also be used to determine other acoustic properties of materials, such as the normal incidence sound absorption coefficient.

The transfer function matrix method is similar to the method described in ASTM E1050-19 and ISO 10534-2, where an impedance tube is used with a broadband sound source connected to one end of the tube and the material sample mounted in the middle part of the tube. The difference is that the transfer function matrix method uses four microphones, two on each side of the material sample with diaphragms flushed to the inside surface of the impedance tube (Fig. 7). These microphones simultaneously measure the sound pressure levels at all four locations including their relative amplitudes and phases. The method requires at least one microphone and a two-channel analyzer, but employing more microphones and channels speeds up the measurement procedure. Allowable measurement configurations and procedures are shown in Table 1.



Legend: A, B, C and D are the forward and backward components of the standing wave

Fig. 7 Measurement setup for transfer function matrix method [28]

Table 1 Measurement configurations and procedures [28]

Number of channels	Number of microphones	Transfer function reference	Measured transfer function	Procedure
2	1	source signal	$\underline{H}_{1s}, \underline{H}_{2s}, \underline{H}_{3s}, \underline{H}_{4s}$	single microphone moves to locations 1–4
2	2	mic. 1 at location 0	$\underline{H}_{10}, \underline{H}_{20}, \underline{H}_{30}, \underline{H}_{40}$	microphone 2 moves to locations 1–4
2	2	mic. 1 at location 1	$\underline{H}_{11} = 1, \underline{H}_{21}, \underline{H}_{31}, \underline{H}_{41}$	microphone 2 moves to locations 2–4
4	4	mic. 1 at location 1	$\underline{H}_{11} = 1, \underline{H}_{21}, \underline{H}_{31}, \underline{H}_{41}$	fixed microphones in locations 1–4
5	4	source signal	$\underline{H}_{1s}, \underline{H}_{2s}, \underline{H}_{3s}, \underline{H}_{4s}$	fixed microphones in locations 1–4
5	5	mic. 1 at location 5	$\underline{H}_{10}, \underline{H}_{20}, \underline{H}_{30}, \underline{H}_{40}$	fixed microphones in locations 1–4

The acoustic properties of the material are determined based on the transfer function matrix formed from the measurements of complex sound pressures at the microphone positions. Practically, the transfer function between the reference position and other microphone positions is determined based on the corresponding auto spectra and cross spectra (see Eq. (8)). The transfer function matrix relates the sound pressure and the particle velocity on the front and back surface of the test material sample:

$$\begin{bmatrix} \underline{p} \\ \underline{u} \end{bmatrix}_{x=0} = \begin{bmatrix} \underline{T}_{11} & \underline{T}_{12} \\ \underline{T}_{21} & \underline{T}_{23} \end{bmatrix} \begin{bmatrix} \underline{p} \\ \underline{u} \end{bmatrix}_{x=d} . \tag{11}$$

The acoustic standing wave formed on both sides of the test material sample is decomposed into components A, B, C and D, as indicated in Fig. 7, based on the following equations [28]:

$$\underline{A} = j\,\frac{\underline{H}_{1,\mathrm{ref}}\,e^{-jkl_1} - \underline{H}_{2,\mathrm{ref}}\,e^{-jk(l_1-s_1)}}{2\sin(ks_1)} , \tag{12}$$

$$\underline{B} = j\,\frac{\underline{H}_{2,\mathrm{ref}}\,e^{jk(l_1+s_1)} - \underline{H}_{1,\mathrm{ref}}\,e^{jkl_1}}{2\sin(ks_1)} , \tag{13}$$

$$\underline{C} = j\,\frac{\underline{H}_{3,\mathrm{ref}}\,e^{jk(l_2+s_2)} - \underline{H}_{4,\mathrm{ref}}\,e^{jkl_2}}{2\sin(ks_2)} , \tag{14}$$

$$\underline{D} = j\,\frac{\underline{H}_{4,\mathrm{ref}}\,e^{-jkl_2} - \underline{H}_{3,\mathrm{ref}}\,e^{-jk(l_2-s_2)}}{2\sin(ks_2)} . \tag{15}$$

The sound pressure and the particle velocity on both faces of the test material sample are determined as [28]:

$$\begin{aligned} &\underline{p}_{x=0} = \underline{p}_0 = \underline{A}+\underline{B}, \qquad \underline{p}_{x=d} = \underline{p}_d = \underline{C}e^{-jkd} + \underline{D}e^{jkd}, \\ &\underline{u}_{x=0} = \underline{u}_0 = \frac{\underline{A}-\underline{B}}{\rho c}, \qquad \underline{v}_{x=d} = \underline{v}_d = \frac{\underline{C}e^{-jkd} - \underline{D}e^{jkd}}{\rho c}. \end{aligned} \tag{16}$$

Distances l_1, l_2, s_1, s_2 and d in eq. (12-16) are indicated in Fig. 7.

The elements of the transfer function matrix are determined from two measurements with two different terminations: the recommended anechoic termination or termination with minimum reflection (termination "a"), and the rigid (blocked) or open termination, reflecting part of the incident wave (termination "b").

Then, the transfer function matrix is [28]:

$$T = \begin{bmatrix} \dfrac{\underline{p}_{0\mathrm{a}}\underline{u}_{d\mathrm{b}} - \underline{p}_{0\mathrm{b}}\underline{u}_{d\mathrm{a}}}{\underline{p}_{d\mathrm{a}}\underline{u}_{d\mathrm{b}} - \underline{p}_{d\mathrm{b}}\underline{u}_{d\mathrm{a}}} & \dfrac{\underline{p}_{0\mathrm{b}}\underline{p}_{d\mathrm{a}} - \underline{p}_{0\mathrm{a}}\underline{p}_{d\mathrm{b}}}{\underline{p}_{d\mathrm{a}}\underline{u}_{d\mathrm{b}} - \underline{p}_{d\mathrm{b}}\underline{u}_{d\mathrm{a}}} \\ \dfrac{\underline{u}_{0\mathrm{a}}\underline{u}_{d\mathrm{b}} - \underline{u}_{0\mathrm{b}}\underline{u}_{d\mathrm{a}}}{\underline{p}_{d\mathrm{a}}\underline{u}_{d\mathrm{b}} - \underline{p}_{d\mathrm{b}}\underline{u}_{d\mathrm{a}}} & \dfrac{\underline{p}_{d\mathrm{a}}\underline{u}_{0\mathrm{b}} - \underline{p}_{d\mathrm{b}}\underline{u}_{0\mathrm{a}}}{\underline{p}_{d\mathrm{a}}\underline{u}_{d\mathrm{b}} - \underline{p}_{d\mathrm{b}}\underline{u}_{d\mathrm{a}}} \end{bmatrix} . \tag{17}$$

If the material sample is geometrically symmetrical, the measurement procedure can be simplified with only one termination, preferably anechoic (often called the two-cavity method). In this case, the transfer function matrix is [28]:

$$T = \begin{bmatrix} \dfrac{\underline{p}_d \underline{u}_d + \underline{p}_0 \underline{u}_0}{\underline{p}_0 \underline{u}_d + \underline{p}_d \underline{u}_0} & \dfrac{\underline{p}_0^2 - \underline{p}_d^2}{\underline{p}_0 \underline{u}_d + \underline{p}_d \underline{u}_0} \\ \dfrac{\underline{u}_0^2 - \underline{u}_d^2}{\underline{p}_0 \underline{u}_d + \underline{p}_d \underline{u}_0} & \dfrac{\underline{p}_d \underline{u}_d + \underline{p}_0 \underline{u}_0}{\underline{p}_0 \underline{u}_d + \underline{p}_d \underline{u}_0} \end{bmatrix}. \tag{18}$$

Finally, the normal incidence sound absorption coefficient is determined as:

$$\alpha_\text{n} = 1 - \left| \frac{\underline{T}_{11} - \rho c \underline{T}_{21}}{\underline{T}_{11} + \rho c \underline{T}_{21}} \right|^2 . \tag{19}$$

The transfer function matrix method with four microphones is more suitable for materials with low flow resistivity [29]:

The usable frequency range of the standard impedance tube is limited to 6.4 kHz based on the microphone spacing and impedance tube diameter. However, a newly developed high-frequency impedance tube can measure the acoustic characteristics of materials up to 12.8 kHz [30]. In the paper [30], this impedance tube was verified and the obtained results were compared with those from conventional impedance tubes.

3.4. Transfer function method with two microflowns

The development of a novel particle velocity sensor, the microflown, enabled the application of the transfer function method using two microflowns and a measurement setup similar to the one shown in Fig. 4. The positions for microphones in Fig. 4 are used for the microflowns. In order to determine the normal incidence sound absorption coefficient, the transfer function between the two microflowns must be determined:

$$\alpha_\text{n} = 1 - \left| \frac{e^{jk(x_1 - s)} - \underline{H}_{12} e^{jkx_1}}{e^{-jk(x_1 - s)} - \underline{H}_{12} e^{-jkx_1}} \right|^2 , \tag{20}$$

where $\underline{H}_{12}$ is the transfer function between two microflowns position 1 and 2:

$$\underline{H}_{12} = \frac{\underline{u}_2}{\underline{u}_1} = \frac{\underline{S}_{12}}{\underline{S}_{11}} = \frac{\underline{S}_{22}}{\underline{S}_{21}} = \sqrt{\frac{\underline{S}_{12}}{\underline{S}_{11}} \cdot \frac{\underline{S}_{22}}{\underline{S}_{21}}} . \tag{21}$$

The method is described in [31, 32].

3.5. P-U method

The combination of a microphone and a microflown provides information about the sound intensity and sound energy density. Fahy [33] showed that the ratio between the mean sound intensity and the mean sound energy density is related to the amplitude reflection coefficient:

$$\frac{\overline{I}}{\overline{E}} = c\frac{1-|\underline{r}|^2}{1+|\underline{r}|^2} \,. \tag{22}$$

The normal incidence sound absorption coefficient of the material sample can be calculated as:

$$\alpha_\mathrm{n} = \frac{\overline{E}c - \overline{I}}{\overline{E}c + \overline{I}}\cos(2kL) \,. \tag{23}$$

The impedance tube configuration for p-u method is shown in Fig. 8, where the microphone and the microflown positions are indicated by *p* and *v*.

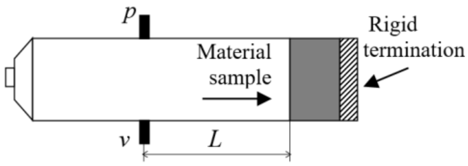


Fig. 8 Impedance tube configuration for p-u method

Using two channel FFT analyzer, the mean sound intensity and the mean sound energy density can be calculated by measuring auto spectra and cross spectra as [31]:

$$\overline{E} = \frac{1}{2}\rho_0 S_{uu} + \frac{1}{2\rho_0 c^2} S_{pp} \,. \tag{24}$$

$$\overline{I} = \mathrm{Re}\{\underline{S}_{pu}\} \,. \tag{25}$$

Replacing eq. (24) and eq. (25) in eq. (23), the normal incidence sound absorption coefficient of material sample can be calculated based on auto spectra and cross spectra measurement.

4. Relationship between Impedance Tube and Reverberation Room Methods

In chapters 2 and 3, different methods for measuring sound absorption coefficient were outlined. The methods discussed in chapter 2 provide the random incidence sound absorption coefficient, while those in chapter 3 provide the normal incidence sound absorption coefficients. Converting sound absorption coefficients is not easy but is very useful. The impedance tube methods are conducted in a controlled environment on small samples, which is ideal when developing new absorption materials and validating prediction models. On the other hand, the random incidence sound absorption coefficient is the parameter most used in the design of spaces to specify the absorption performance of materials [1].

There are different approaches to solving this problem: a theoretical approach and an empirical approach and combination of both.

In the theoretical approach [34, 35], the random incidence sound absorption coefficient is determined based on the characteristic impedance measurement in the impedance tube.

All methods outlined in chapter 3 provide determining the characteristic impedance of the test material. The random incidence sound absorption coefficient is determined using the following equations [34]:

$$\alpha_r = 2\int_o^{\pi} \alpha(\theta)\,\sin\theta\cos\theta\ , \tag{26}$$

$$\alpha(\theta) = \frac{4R_n\cos\theta}{(1+R_n\cos\theta)^2 + (X_n\cos\theta)^2}\ , \tag{27}$$

where

- θ is the sound incidence angle, in [rad];
- R_n is the real part of the normal sound incidence normalized characteristic impedance;
- X_n is the imaginary part of the normal sound incidence normalized characteristic impedance.

Solving eq (26), an expression to estimate the random sound incidence absorption coefficient is obtained [36]:

$$\alpha_r = 8\frac{R_n}{R_n^2+X_n^2}\left[1-\frac{R_n}{R_n^2+X_n^2}\ln(1+2R_n+R_n^2+X_n^2)+\frac{1}{X_n}\frac{R_n^2-X_n^2}{R_n^2+X_n^2}\arctan\frac{X_n}{1+R_n}\right]. \tag{28}$$

Fig. 9 shows the comparison between the random incidence sound absorption coefficients obtained in a reverberation room and those estimated from eq. (28) for recycled foam with a density of 150 kg/m^3 and thickness of 40 mm.

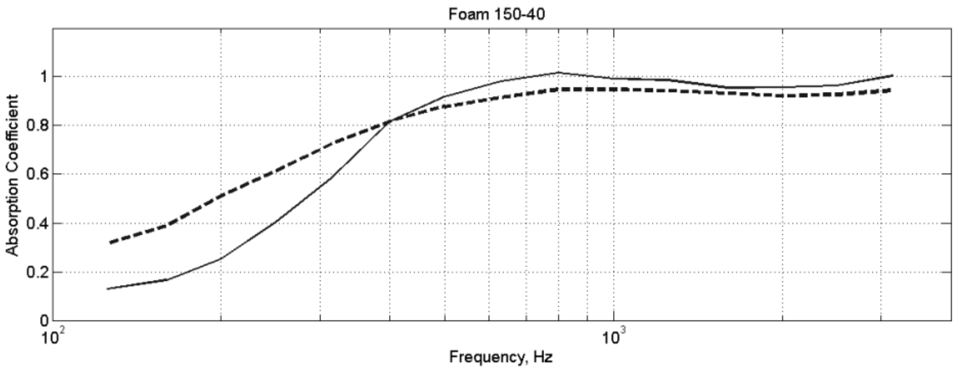


Fig. 9 Comparison between measured (continuous line) and estimated (dotted line) random incidence sound absorption coefficient [35]

In the experimental approach [10], the relationship between the random incidence absorption coefficient and the normal incidence absorption coefficient is established based on measurement results for 28 polyester samples tested using the reverberation room interrupt method and the transfer function impedance tube method. The predicted random incidence sound absorption coefficient can be calculated based on the measured normal incidence sound absorption coefficient using the equation [10]:

$$\alpha_{\mathrm{r}}(f) = 0.945 + 0.245\ \ln\alpha_{\mathrm{n}} + \phi(f) - 0.002\rho + 0.0015d + 7.52e^{-6}R\ . \qquad (29)$$

where

ρ is the density of the material sample, in [kg/m^3];

d is the thickness of the material sample, in [m];

X_{n} is the flow resistivity of the material sample, in [Pa·s/m^3];

$\phi(f)$ are the frequency factor coefficients shown in Table 2 [10].

Fig. 10 shows the comparison between the random incidence sound absorption coefficients obtained in a reverberation room and those estimated from eq. (29) for two polyester samples.

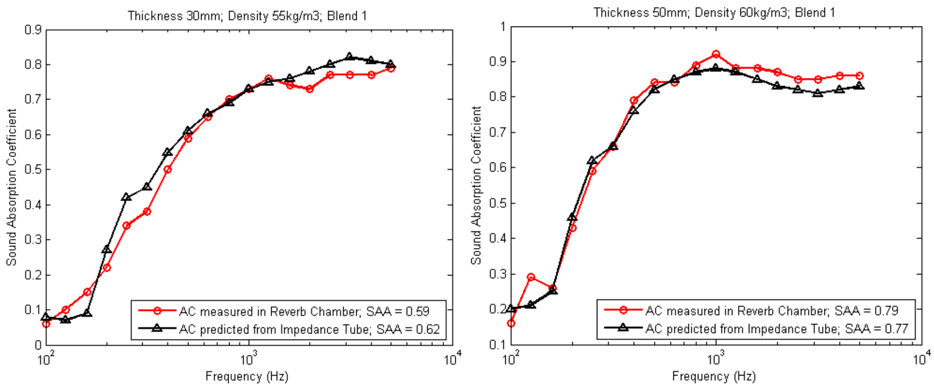


Fig. 10 Comparison between measured and estimated random incidence sound absorption coefficient (adopted from [10])

5. CONCLUSIONS

The absorption performances of acoustic materials can be characterized by four interrelated acoustic quantities: surface impedance, surface admittance, sound reflection coefficient and sound absorption coefficient. Knowledge of these four acoustic quantities is fundamental for calculating noise reduction using sound absorption materials and for the acoustic design of spaces depending on their purpose.

While there are well-known theoretical models for characterizing sound absorption materials, numerous methods have been developed over the years to measure acoustic quantities that define sound absorption materials. The most commonly used methods are two standardized approaches: the reverberation room method and the incidence tube method.

The reverberation room method is exclusively used for determining the random incidence sound absorption coefficient, an acoustic quantity frequently employed in design to specify the absorption performance of materials. To apply the reverberation room method, it is necessary to have a diffuse sound field in the room, where the interrupt noise method and integrated impulse response method can be used.

Despite its popularity in determining the random incidence sound absorption coefficient, the reverberation room method has certain disadvantages:

- other acoustic characteristics of the sound absorption material, except the sound absorption coefficient, cannot be determined;
- large and expensive facilities are required;
- large samples are required which are not always available, especially in the material development phase;
- the position and size of the sample can influence the results;
- sound absorption coefficient values are often overestimated and higher than 1, due to edge diffraction, non-diffuseness, and/or Sabine formulation;
- significant differences in results may occur for different reverberation rooms.

The impedance tube method provides the surface impedance, the surface admittance, the sound reflection coefficient and the sound absorption coefficient. The measurement is carried out under well-defined and controlled conditions and can be frequently used in the development of new sound absorption materials and validation of prediction methods. The advantage of this method is that it requires only small samples and relatively simple instrumentation that can be placed in a normal room. The time and costs of testing are far less compared to the reverberation room method. The problem in applying this method arises when small samples are not representative of the behavior of large samples, so it is most often used with porous absorbers. Different types of measuring the acoustic properties of materials using an impedance tube are outlined in this paper. The transfer function matrix method is primarily intended for determining normal incident sound transmission loss, but it can also be used to determine other acoustic properties of materials such as the normal incidence sound absorption coefficient.

The investigation results of the sound absorption characteristics of single and multi-layered porous materials show that the standing wave method is simpler, but the transfer function method and the transfer function matrix method are more accurate.

The investigation results obtained applying the two-microphone transfer function method show that this method can also be used for determining the absorption characteristics of the new composite materials [3].

The reverberation method provides the random incidence sound absorption coefficient, while the impedance tube method provides the normal incidence sound absorption coefficient. Although converting sound absorption coefficients is not easy, it can be very useful. Applying the available theoretical and empirical approaches for converting the measurement results obtained in the impedance tube into the random incidence sound absorption coefficient, good agreement between the predicted and measured random incidence sound absorption coefficient can be obtained.

Acknowledgement: *This research was sponsored by the NATO Science for Peace and Security Programme under grant SPS MYP G6006 "Acoustic Multi-Functional Composites for Environmental Risks and Health Hazards Reduction" and by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under the contract no. 451-03-66/2024-03/200148.*

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METODE ZA MERENJE KOEFICIJENTA APSORPCIJE ZVUKA U REVERBERACIONOJ PROSTORJI I IMPEDANSNOJ CEVI

Zvučno-apsorpcioni materijali se veoma često koriste za projektovanje prostora u cilju smanjenja nivoa buke i podešavanja akustičkih karakteristika prostora u zavisnosti od njegove namene. Stoga je poznavanje akustičkih veličina koje karakterišu zvučno-apsorpcione materijale od ključnog značaja. Najčešće korišćena akustička veličina je koeficijent apsorpcije zvuka koja se može odrediti primenim standardizovanih metoda i metoda koje se koriste samo za istraživačke svrhe. U ovom radu će biti dat pregled najčešće korišćenih standardizovanih metoda za određivanje koeficijenta apsorpcije zvuka: metod reverberacione prostorije i metod impedansne cevi. Kako je u fazi razvoja novih materijala pogodnija primena metode impedansne cevi koja daje koeficijent apsorpcije zvuka pri normalnoj incidenciji, a u praktičnoj primeni je poželjno poznavanje koeficijenta apsorpcije zvuka pri slučajnoj incidenciji, u ovom radu će biti prikazani pristupi za predikciju koeficijenta apsorpcije zvuka pri slučajnoj incidenciji na osnovu merenja akustičkih parametara zvučno-apsorpcionih materijala u impedansnoj cevi.

Ključne reči: *koeficijent apsorpcije zvuka pri slučajnoj incidenciji, koeficijent apsorpcije zvuka pri normalnoj incidenciji, metod reverberacione prostorije, metod impedansne cevi*.