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Sound Diffusers with Fabric Covering

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Fabric covering is often used by designers, as it can easily mask acoustic structures that do not match an interior. However, in the case of sound diffusers based on change in the phase of the reflected wave, the use of fabric covering is not without its effect on acoustics. It reduces the effectiveness of these structures and raises acoustic absorption. In the paper, the authors analyzed the acoustical properties of a selected fabric used to cover sound diffusers. Sound absorption and scattering coefficients for a system composed of sound diffusers and a fabric situated at different distances d were measured. The results were compared to the sound absorption predicted on the basis of Kuttruff's and Mechel's theoretical models. Analysis of the results indicates that the fabric has a significant influence on the system's acoustic parameters. It is also observed, that fabric applied directly on a phase grating diffuser, produces higher absorption than when it is at some distance from it.

Keywords: fabric covering, Schroeder diffusers, absorption, scattering.

1. Introduction

In room acoustics, the most important property of the material is the absorption coefficient introduced by Sabine (1922). Despite the many corrections that have been introduced to the reverberation time formula, Sabine's basic equation, which is based only on geometry and the absorption coefficient, is still widely used, not only by non-professionals. However, the Sabine's formula does not always give precise results. Initially, the method of sound absorption coefficient averaging was investigated (Eyring, 1930). How materials are distributed was then accounted for a theoretical model (Fitzroy, 1959). No new acoustic parameter describing the reflection from walls was proposed until 1976 (Kuttruff, 1976), when Kuttruff reckoned with the fact, that reflections from walls are not purely specular, a fact which influences the reverberation time. Three years later, Schroeder (1979) found that diffuse reflections are desirable, especially those from the ceiling in low concert halls. In that paper, Schroeder showed that reflection from a structure will be diffuse, if phase shifts of the waves reflected from small parts of the structure are random. On the basis of the number theory, he proposed a quadratic-residue sequence to shape the depth of the structure. Being easy to apply and giving high diffusion over a wide frequency band, quadratic-residue diffusers (QRD) became very popular.

Nowadays, many interiors of cinemas, television studios, home theatres, and philharmonic halls are equipped with some kind of diffusers. Sometimes they are in harmony with the room's design, while in historical rooms, specialist acoustics structures do not match the interior. In such cases, they are often concealed behind an acoustically transparent fabric, to mask the acoustic structure without changing its properties. However, as might be expected, transparency applies only to a covering used on highly absorptive materials. A different approach is needed in masking structures with low absorption coefficients and special care should be taken especially where QRDs are concerned. This type of diffuser was designed to reflect evenly in every direction as much sound as possible. Fujiwara and Miyajima (1992) were the first to measured the absorption of diffusers which greatly exceeded the expected value. The first attempt to explain this phenomenon was made by Kuttruff (1994). In his calculation Kuttruff assumed a constant sound pressure on the plane of the diffuser. His theoretical model results in a too low absorption. A year later, Mechel (1995) developed a much more complex model and showed that absorption is caused not only by viscous and thermal losses, but also by the flow of air between adjacent wells of the diffuser. He was also the first to calculate and measure the influence of resistive layers situated on the entrances of the wells on the absorption coefficient. Based on his approach, Wu *et al.* (2000) pointed out the possibility of creating a highly absorptive structure that would combine the QRD and a resistive covering.

The goal of this study is to show the influence of resistive layers on acoustic parameters (absorption and scattering coefficient) of diffusers. Ways of minimizing the additional absorption from a textile covering are also investigated.

2. Prediction of sound absorption

2.1. Absorption of a resistive layer above a rigid plate

Let us consider the absorption of a resistive layer above a rigid plate. The equivalent interaction impedance of a flexible single screen with cavity backing z_e can be expressed as a parallel combination of the interaction impedance z and the structural impedance z_s (Ingard, 1994):

$$z_e = z z_s/(z + z_s). \tag{1}$$

For a limp sheet, there is $z_s = -i\omega m$, where m is the mass per unit area of the sheet. If $z = r + ix$, then

$$z_e = \frac{r(\omega m)^2}{r^2 + (\omega m - x)^2} - i\omega m \frac{r^2 - x(\omega m - x)}{r^2 + (\omega m - x)^2}. \tag{2}$$

According to Wu's assumption (Wu, 2000), textile cover is purely resistive, so the reactance part of z is $x = 0$. For the textile cover used in the measurements, $m = 0.15$ kg/m^2.

The input impedance for a resistive screen over an air layer of thickness d is expressed by

$$Z(\phi) = z_e - \frac{i\cot(k_z d)}{\cos(\phi)}, \tag{3}$$

where $k_z = k_0 \cos(\phi)$ is the normal component of the wave vector $\mathbf{k}_0$ for angle of incidence ϕ. With the input impedance $Z(\phi)$ known, the absorption coefficient $\alpha(\phi)$ is expressed according to (Ingard, 1994) by

$$\alpha(\phi) = \frac{4\mathrm{Re}(Z)\cos\phi}{(1 + \mathrm{Re}(Z)\cos\phi)^2 + (\mathrm{Im}(Z)\cos\phi)^2}. \tag{4}$$

The impedance of textile cover located at different distances d from the rigid plate was measured using an impedance tube. By comparing it with the absorption coefficient for normal incidence $\alpha(0)$ calculated according to (4), the resistance of textile cover was found to be equal $r\rho_0 c = 40$ rayl, where $\rho_0 c$ is the impedance of air.

In order to compare the absorption coefficient of a resistive screen situated over a rigid plane measured in diffuse field and calculated using (4), integration over hemisphere should be done

$$\alpha_{\text{diff}} = 2 \int_0^{\pi/2} \alpha(\phi) \cos\phi \sin\phi \, \mathrm{d}\phi. \tag{5}$$

2.2. Absorption of quadratic residue diffusers

In both Kuttruff's and Mechel's models of sound absorption, the calculation of admittance of a single well is carried out in the same way. In Kuttruff's approach, the absorption of a QRD is calculated by averaging the admittance of each well, while in the Mechel model, mutual interaction between wells is taken into account. The geometry of the analyzed system, composed of diffuser and textile cover, is presented in Fig. 1.

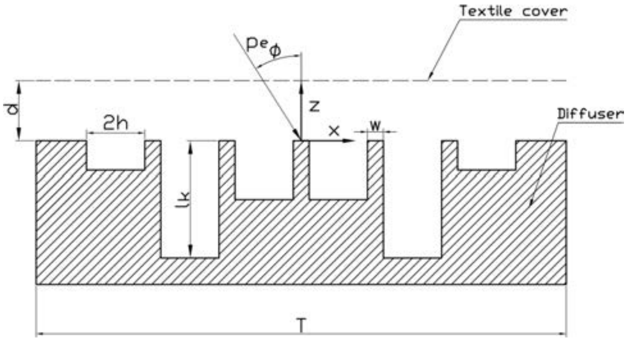

Fig. 1. Geometry of the system composed of a quadratic residue diffuser and textile cover at the distance d.

Normalized input admittance of one well is equal to

$$G(x_k) = \frac{\tanh(\Gamma_w k_0 l_k)}{Z_w}, \tag{6}$$

where $k_0 l_k$ is the Helmholtz number. For a QRD it is calculated according to (Mechel, 1995)

$$k_0 l_k = \frac{f}{f_0}\frac{\pi}{N}\mathrm{mod}(k^2, N); \quad k = 0, 1, \ldots, N-1. \tag{7}$$

Propagation constant Γ_w and wave impedance Z_w in wells (Mechel, 2008) are:

$$\Gamma_w = k_0 j \sqrt{\frac{1 + (\kappa - 1)\dfrac{\tan(k_{\alpha 0} h)}{k_{\alpha 0} h}}{1 - \dfrac{\tan(k_\nu h)}{k_\nu h}}}, \tag{8}$$

$$Z_w = \frac{Z_0}{\sqrt{\left[1 + (\kappa - 1)\dfrac{\tan(k_{\alpha 0} h)}{k_{\alpha 0} h}\right]\left[1 - \dfrac{\tan(k_\nu h)}{k_\nu h}\right]}}, \tag{9}$$

where

$$k_0 = \frac{\omega}{c}, \qquad k_\nu^2 = -j\frac{\omega}{\nu}, \qquad k_{Pr}^2 = \kappa \mathrm{Pr} k_\nu^2, \tag{10}$$

where $\nu = 15 \cdot 10^{-6}$ m^2/s is the kinematic viscosity of air, $\kappa = 1.401$ is the adiabatic exponent and $\mathrm{Pr} = 0.6977$ is the Prandtl number.

With $T = N(2h+w)$, being the width of one period, its average admittance is given by

$$\langle G \rangle = \frac{2h}{T} \sum_{k=0}^{N-1} G(x_k). \tag{11}$$

With the normalized impedance of $Z = 1/\langle G \rangle$, the absorption coefficient can be calculated according to (4).

In Mechel's model (Mechel, 1995), the sound field in front of the diffuser is decomposed into the incident plane wave $p_e(x,y)$ and the scattered field $p_s(x,y)$, which itself is made up of plane waves and higher spatial harmonics:

$$\begin{aligned} p(x,z) &= p_e(x,z) + p_s(x,z), \\ p_e(x,z) &= P_e \exp[j(-xk_x + zk_z)], \\ p_s(x,z) &= \sum_{n=-\infty}^{+\infty} A_n \exp(-\gamma_n z) \exp(-j\beta_n x), \end{aligned} \tag{12}$$

where the wave numbers are

$$\begin{aligned} k_x &= k_0 \sin\phi_e = \beta_0, \\ k_z &= k_0 \cos\phi_e, \\ \beta_n &= \beta_0 + n\frac{2\pi}{T}, \\ \gamma_n &= k_0\sqrt{(\sin\phi_e + n\lambda_0/T)^2 - 1}. \end{aligned} \tag{13}$$

The wells' admittance is first transformed by Fourier analysis

$$g_n = \frac{1}{T}\int_0^T G(x) \exp\left(jn\frac{2\pi}{T}\right) \mathrm{d}x \tag{14}$$

and the amplitudes A_n of the spatial harmonics are then calculated

$$\sum_{n=-N}^{+N} A_n \left[g_{-m-n} - j\delta_{m,-n}\frac{\gamma_n}{k_0} \right] = P_e(\delta_{m,0}\cos\phi_e - g_{-m}), \qquad m = -N, \ldots, +N, \tag{15}$$

where $\delta_{m,n}$ is the Kronecker symbol.

The absorption coefficient including higher spatial harmonics is

$$\alpha(\phi_e) = 1 - \left|\frac{A_0}{P_e}\right|^2 - \frac{1}{\cos\phi_e}\sum_{n_s \neq 0}\left|\frac{A_{ns}}{P_e}\right|^2 \cdot \sqrt{1 - (\sin\phi_e + n_s\lambda_0/T)^2}, \tag{16}$$

where $P_e = 1$ is the amplitude of the incident wave and n_s, as indices of spatial harmonics, are determined by the condition

$$-\frac{T}{\lambda_0}(1 + \sin\phi_e) \le n_s \le \frac{T}{\lambda_0}(1 - \sin\phi_e). \tag{17}$$

Only theoretical models for calculating the absorption coefficient are presented – there is no reliable model to calculate the scattering coefficient. The diffusion coefficient obtained in free field can be accurately predicted, because its definition and the method of measurement are in agreement with the physical phenomenon. On the other hand, measuring the scattering coefficient involves determining the difference between the absorption of a rotating and a stationary sample. Physically, absorption is the same, but due to the integrated impulse response method used in the measurement, the results are different because of non-specular reflection from the sample.

3. Measurement system

The measurements were conducted in Laboratory of Technical Acoustics' reverberation chamber at the Department of Mechanics and Vibroacoustics, AGH in Krakow. The chamber volume is $V = 180.4$ m^3, the total area of the walls is $S = 193.7$ m^2.

To measure the sound absorption coefficient, two omni-directional sound sources were used, powered by the CREST CPX 2600 amplifier, which received the input signal from an NI PXI-4461 card output. Signals were recorded using six GRAS 46AQ microphones connected to an NI PXIe-4496 card. An application was developed in the LabVIEW environment to generate the measurement signal, record the response of the room and determine the impulse responses. A wideband modulated test signal (sine sweep) was used. Temperature and humidity were measured using an LB-701H thermohygrometer controlled directly by the LabVIEW module.

When measuring the scattering coefficient in accordance with the ISO 17491-1 standard, a sample with a diameter of 2.75 m was positioned on a turntable placed on the floor of the reverberation chamber (Fig. 2). The turntable was operated by an NI PXIe-

Fig. 2. The QRD covered with fabric used in the scattering coefficient measurement.

8180 controller. The test signal was generated and the response was recorded using B&K Dirac 4.1 software. A Waveterminal U2A card was used as the I/O interface. An amplifier and an omni-directional sound source were used in the measurements as described above. As a test signal, an MLS was used with a 48000 Hz sampling frequency and a sequence composed of $2^{19}-1$ samples. In both cases the chamber was equipped with five fixed diffusers, selected in accordance with Annex A to ISO 354. The positions of the microphones and sound sources remained unchanged throughout the measurements. The impulse responses of the chamber were determined using signals with a length of 10.9 seconds. On the basis of preliminary measurements, the possibility of using a shorter signal than the maximum length of the reverberation time for some frequencies was verified. Doing so would shorten the measurements during which the ambient conditions should have remained unchanged.

As a diffuser, a one-dimensional pseudo-stochastic periodic surface structure based on the first number $N = 7$ was used with a well width of $2h = 22$ mm, $w = 6$ mm and a maximum depth of $l_{\max} = 44$ mm. A circular sample with a diameter of 2.75 m contained 13.5 periods of sequences. The diffuser was covered with a thin 100% polyester fabric commonly used to cover diffusers, with a surface weight of $m = 0.15$ kg/m^2. The fabric was stretched on a steel rim with a diameter equal to that of the diffuser. Side surfaces were screened by the cover fitted to the total height of the sample.

4. Results

4.1. Sound absorption coefficient

The sound absorption coefficient was measured in accordance with the ISO 354 standard for the following configurations:

a) fabric + sound reflecting surface at a distance of 0, 5, 10 and 14 cm

b) fabric + sound diffuser at a distance of 0, 5 and 10 cm

The results for a) are shown in Fig. 3. In order to improve the readability of the graph, sound absorption values for selected distances d are presented. The results show, that the maximum value of absorption does not change for different distances d, but only shifts along the frequency axis. Good agreement between the theoretical model and measurements was obtained. For all distances, absorption at low frequency is higher than predicted. The maxima occur at similar frequencies, but in the case of measurements, the resonance has smaller $Q = f_r/\Delta f$, where f_r is the resonant frequency, and Δf is the bandwidth. For antiresonance, where the width of the air layer is equal to the half-length of the incident wave, it is almost impossible to observe a minimum in the measured curve.

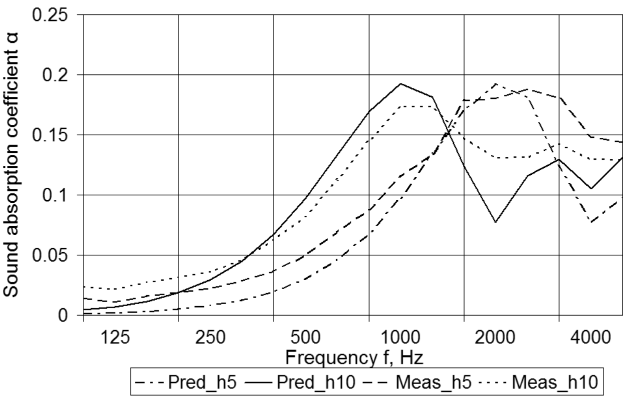

Fig. 3. The sound absorption coefficient for the fabric stretched over the reflecting surface. The number in the legend indicates the distance (in cm) between the fabric and the surface, Pred – prediction, Meas – measurement.

The absorption coefficient of the diffuser with and without fabric stretched over it is shown in Fig. 4. The measurements indicate significant absorption in the 100–1000 Hz range, while prediction based on both models provides values near 0. For higher frequencies both Mechel's and Kuttruff's models predict for the diffuser with fabric covering an increase in absorption for the frequency range (1600–2500 Hz), which is consistent with the measurements. The calculated values of the sound absorption coefficient α are underestimated when calculated according to the Kuttruff model. In the case of the Mechel model, the maximal predicted value is larger than that measured, but the peak has a much bigger Q-factor.

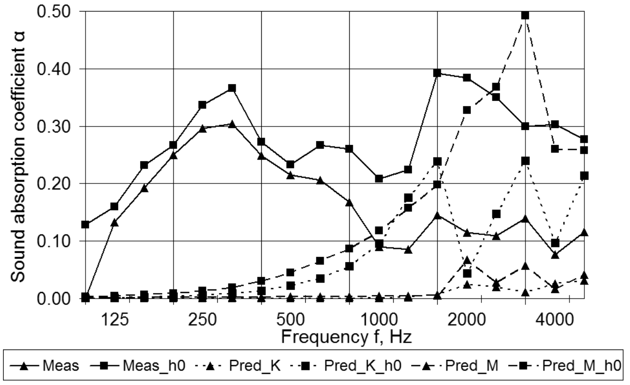

Fig. 4. The sound absorption coefficient for the QRD with and without fabric cover. Prediction based on Kuttruff's and Mechel's model is included. The letter K stands for the Kuttruff model and M for the Mechel model, the line without given height, represents absorption of the diffuser without a fabric covering.

Note the significant increase over the entire frequency range in the absorption of the diffuser with the fabric as compared to that without it (Fig. 5). When

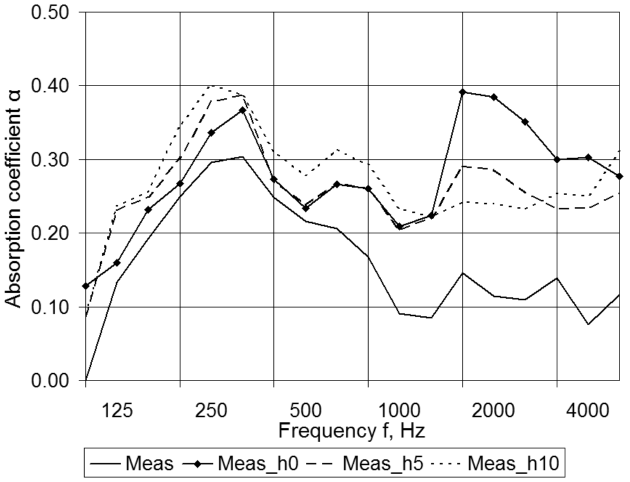

Fig. 5. The sound absorption coefficient for the fabric stretched over the QRD. The number in the legend indicates the distance (in cm) between the fabric and the diffuser. The line without a given height represents the absorption of a diffuser without a fabric covering.

the fabric is placed directly on the diffuser, a noteworthy increase in absorption occurs as compared to distances $d = 5$ cm and $d = 10$ cm, mainly in the 1600–2500 Hz frequency range, where the structure scatters sound the most effectively. For $f = 1600$ Hz the phase shifts between adjacent wells are an integer multiple of $\lambda_0/4 = c/(4f)$, which causes significant airflow between them and gives the highest absorption when resistive material is put on the entrance to the wells.

Among the measured distances between the fabric and diffuser, the smallest absorption occurs at $d = 5$ cm. At $d = 10$ cm, the absorption for frequencies 1600–2500 Hz is the lowest (the fabric cover does not influence the near field of the diffuser), but there is an increase in absorption for the 400–1000 Hz frequency range.

4.2. Sound scattering coefficient

Measurements were conducted to determine the effect of fabric on sound scattering by the fabric-covered diffuser (the results are shown in Fig. 6). ISO standard 17497-1 recommends, that the measurement of the scattering coefficient should be restricted to structures with the sound absorption coefficient α below 0.5. Note that systems composed of the diffuser and the fabric show a greater than or close to 0.5 absorption coefficients in the 250–400 Hz range, and that the authors are aware that the results are characterized by a greater error.

The results show that the fabric has a small effect on sound scattering at low and medium frequencies. In contrast, at higher frequencies the scattering coefficient increases, especially when the fabric is placed directly on the diffuser. In the characteristics shown in Fig. 6, the values of the scattering coefficient exceed 1 for some frequencies. This is acceptable and might be caused by diffraction at the sample edges. The difference in the scattering coefficient for the diffuser with fabric placed directly on its surface may be due to several concurrent factors. The fabric causes additional scattering of reflected sound and interacts with the wells of the diffuser. The error of the measurement method due to the sample's excessive sound absorption in this frequency range may also be significant.

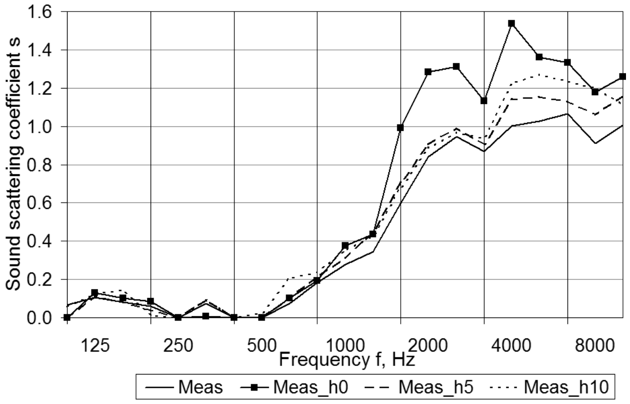

Fig. 6. The sound scattering coefficient for the fabric stretched over the QRD. The number in the legend indicates the distance (in cm) between the fabric and the diffuser. The line without a given height represents the scattering of the diffuser without fabric covering.

5. Conclusion

The paper presents results of studies on the absorption and scattering of a system composed of a fabric covering placed at some distance from diffuser done in remodeling of interiors to improve room acoustics. It was shown that when the reflecting surface is masked, the sound absorption coefficient α is strongly dependent on the properties of the covering fabric (especially its resistance) and the thickness of the air layer between the fabric and reflective surface. While the properties of the fabric determine the maximum value of sound absorption, the air layer affects the frequency, at which the maximum occurs. For QRDs, the most significant change in absorption occurred when the fabric was placed directly on the diffuser's surface. Particularly large differences were observed at frequencies above 1600 Hz. As in the case of the reflecting surface, absorption depends on the resistance of the fabric, but the thickness of the air layer influences not only the position of the maximum, but also its value, especially where the covering is placed close to the diffuser. The results of the measurements showed a significant increase in the sound scattering coefficient for frequencies above 1250 Hz, with much higher results when the fabric was placed directly on the surface of the diffuser surface. This may be attributable to an error in the method, which requires structures with a sound absorption coefficient $\alpha \leq 0.5$. No significant differences were observed at lower frequencies.

The results lead to the conclusion that stretching the fabric directly on the surface of the diffuser, significantly affects its acoustic performance, mainly sound absorption. This conclusion is of particular importance for the interior equipment of music halls (KAMISIŃSKI, 2010), where sound diffusers are important elements and where fabric covering may adversely reduce the acoustic energy of the first reflection. When the reflective plane is covered, the lowest absorption is obtained when fabric is laid directly on the plane. For QRDs, the lowest absorption was observed for air layer of thickness $d = 5$ cm. To further reduce of the absorption coefficient of diffusers, stiffening the construction and reducing the height/width ratio should be considered (PILCH, KAMISIŃSKI, 2011). It can be concluded that even a very light fabric covering can affect the absorption and scattering characteristics of sound diffusers and caution is advised in using fabric covering intuitively.

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