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A theoretical study on the effect of a permeable membrane in the air cavity of a double-leaf microperforated panel space sound absorber

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ABSTRACT

A double-leaf microperforated panel absorber (DLMPP) is composed of a two microperforated panel (MPP) with a air cavity in-between, and without any backing structure. It shows a Helmholtz-type resonance peak absorption and additional low frequency absorption, therefore it can be used as a wideband space sound absorber. In this study, a theoretical study is made to examine the effect of a permeable membrane inside the air-cavity. Permeable membranes are studied in our previous studies and proved to be effective to improve the sound absorption performance of various type MPP sound absorbers. We investigate the absorption characteristics of a DLMPP with a permeable membrane in the cavity through numerical examples, and also studied the effect of honeycomb in the cavity of the same sound absorption structure.

1. Introduction

For a sound absorption treatment porous absorbents are used in many cases, though porous absorbents have hygiene, durability and recyclability problems. As alternative sound absorbing materials, various types of new sound absorption materials have been proposed. Among them a microperforated panel (MPP) [1-4] and membrane materials [5-10] are most promising and widely recognized. Especially, many researchers have been studying MPPs and their applications. An MPP is a panel/film made of metal or plastic sheet with submillimetre perforations, and has great advantage in designability , durability and hygiene considerations.

Usually MPPs are placed parallel with a rigid-back wall with an air-cavity in-between: In this construction Helmholtz resonators are formed with each perforation and back cavity, which produces a Helmholtz resonator type sound absorption. However, in this setting the MPP's sound absorption depends only on the above resonance system, which results in rather limited sound absorption frequency range. Therefore, so far many studies have been made to explore the method to make it more wide-band, both in the case with a back wall and without back wall [1,2, 11-14]. In these studies the authors have proposed a double-leaf MPP space sound absorber (DLMPP) which is composed of two MPP leaves and without any backing structure [12,13]. DLMPP shows a resonance peak absorption of Helmholtz type as well as additional absorption at low frequencies due to its acoustic permeability, which makes it more wideband absorber.

Besides, for improving the absorption performance of MPP absorbers and reducing the cost problems, the authors have proposed sound absorbers composed by a combination of an MPP and a permeable membrane (PM). One is the space sound absorber with combination of an MPP and a PM [14] and the other is the combination absorber backed by a rigid-back wall [15]. In these studies, it is shown that the PM helps to improve the sound absorption performance of MPP type absorbers.

From the above studies, a combination of an MPP and a PM can be promising as improvement of sound absorption performance. There are also some other combination of these materials that should be studied. Therefore, in the present work, in order to improve the sound absorption performance of a DLMPP, the effect of a PM in the air-cavity of a DLMPP is theoretically analysed, and discussed through numerical examples. The sound absorption mechanism is also discussed. As an additional consideration the effect of a honeycomb in the cavity of the above DLMPP plus PM absorber is studied. A honeycomb is known to be effective not only to reinforce the structure but also to improve the sound absorption [16, 17].

2. Theoretical Considerations

2.1 Model for analyses

Figure 1 shows the model for analyses of a triple-leaf structure made of a DLMPP with a PM inside the air-cavity (M-P-M absorber), lying in the x-y plane and of infinite extent. A plane sound wave of unit pressure amplitude impinges with an angle θ. The MPP on the illuminated side is called MPP1 and one on the transmission side is called MPP2 hereafter. Both MPP1 and 2 have the following parameters: the thicknesses $t_{1,2}$ (mm), the hole diameters $d_{1,2}$ (mm), and the perforation ratios $p_{1,2}$ (%), respectively. The PM has the following parameters: the flow resistance R (Pa s/m), the surface density M (kg/m^2) and the tension T (N/m), respectively. The specific acoustic impedance and the displacement of the sound induced vibration of MPP1 are Z_1 and $w_1(x)$, respectively. Those of the PM are Z_2 and $w_2(x)$, respectively. Those of MPP2 are Z_3 and $w_3(x)$, respectively. The depth of the air-cavity between MPP1 and PM is D_1, and that between PM and MPP2 is D_2. The time factor $\exp(-i\omega t)$ is suppressed throughout. The all impedances used in the present analyses are normalised by the characteristic impedance of the air $\rho_0 c_0$ (ρ_0 is the air density (1.2 kg/m^3), c_0 is the sound speed in the air (340 m/s)).

According the Maa's theory [2] the specific acoustic impedance of the MPP, Z_{MPP}, is derived with the acoustic resistance r and acoustic reactance ωm as follows:

$$Z_{\mathrm{MPP}} = r - i\omega m \tag{1}$$

where,

$$r = \frac{32\eta t}{p\rho_0 c_0 d^2}\left(\sqrt{\frac{K^2}{32}+1}+\frac{\sqrt{2}}{8}K\frac{d}{t}\right) \tag{2}$$

$$\omega m = \frac{\omega t}{pc}\left(1+\frac{1}{\sqrt{9+K^2/2}}+0.85\frac{d}{t}\right) \tag{3}$$

$$K = d\sqrt{\frac{\omega\rho_0}{4\eta}} \tag{4}$$

The specific acoustic impedance of the PM, Z_{PM}, is expressed as:

$$Z_{PM} = \frac{R}{\rho_0 c_0} \tag{5}$$

where ω is the angular frequency, η is the viscosity coefficient (1.789×10^{-5}[Pa s]). Here, Z_{PM} is the acoustic impedance when the PM is immovable, i.e., the flow resistance. The sound induced vibration of the leaves (including both the MPPs and PM) is taken into account by introducing the equation of the vibration of the leaves: the equations of the sound field and the equations of the vibration are solved simultaneously.

2.2 Analyses based on Helmholtz-Kirchhoff integrals

First, the sound field in the Domain [I] is analysed. the sound pressure on the illuminated side surface of MPP1, p_{d1}, is expressed as follows by using a Helmholtz-Kirchhoff integral formula:

$$p_{d1}(x,0) = 2p_i(x,0) + \frac{i}{2}\int_{-\infty}^{\infty}\frac{\partial p_1(x_0,0)}{\partial n}H_0^{(1)}(k_0|x-x_0|)dx_0 \tag{6}$$

where, p_{i} is the pressure of the incident wave, n is the normal vector outward from the region, $H_0^{(1)}$ is a Hankel function of the first kind of order zero. The boundary condition on the surface is:

$$\frac{\partial p_{d1}(x_0,0)}{\partial n} = \rho_0\omega^2 w_1(x_0) + iA_{m1}k_0\Delta P_1(x_0) \tag{7}$$

Here, $A_{\mathrm{m1}}=\rho_0 c_0/Z_1$, k_0 is the wavenumber in the air, ΔP_1 is the pressure difference between the both side surface of MPP1, and here Z_1 is substituted with Z_{MPP} eq. (1). From these equations, the pressure on the illuminated side surface of MPP1 is expressed as follows:

$$p_{s1}(x,0) = 2p_i(x,0) + \frac{i}{2}\int_{-\infty}^{\infty}[\rho_0\omega^2 w_1(x_0) + iA_{m1}k_0\Delta P_1(x_0)]H_0^{(1)}(k_0|x-x_0|)dx_0 \quad (8)$$

The sound pressure and particle velocity in the Domains [II] and [III], $p_{d2,3}$, are derived from the general form of a plane wave sound field, which are:

$$p_{d2,3}(x,z) = (X_{2,3}e^{ik_0 z\cos\theta} + Y_{2,3}e^{-ik_0 z\cos\theta})e^{ik_0 x\sin\theta} \quad (9)$$

$$v_{2,3}(x,z) = \frac{\cos\theta}{\rho_0 c_0}(X_{2,3}e^{ik_0 z\cos\theta} - Y_{2,3}e^{-ik_0 z\cos\theta})e^{ik_0 x\sin\theta} \quad (10)$$

where $X_{2,3}$ and $Y_{2,3}$ are the amplitudes of the sound waves in the cavity propagating into $+z$ and $-z$ directions, respectively. When a honeycomb is applied in a cavity, considering that the wave in that cavity propagates into only +/- z directions (θ=0), θ=0 is substituted into $\cos\theta$ in the right hand side, i.e., $\cos\theta$=1.

The boundary conditions are as follows:

$$v_2(x,0) = -i\omega w_1(x) + \frac{\Delta P_1(x)}{Z_1} \quad (11)$$

$$v_2(x,D_1) = -i\omega w_2(x) + \frac{\Delta P_2(x)}{Z_2} \quad (12)$$

$$v_3(x,D_1) = -i\omega w_2(x) + \frac{\Delta P_2(x)}{Z_2} \quad (13)$$

$$v_3(x,D_1+D_2) = -i\omega w_3(x) + \frac{\Delta P_3(x)}{Z_3} \quad (14)$$

where, ΔP_2 and ΔP_3 are the differences of the pressure of the two sides surfaces of the PM and MPP2, respectively, and here Z_1 and Z_3 are substituted with Z_{MPP} in eq. (1), Z_2 is substituted with Z_{PM} in eq. (6).

From eqs. (11)…(14), one can obtain $X_{2,3}$ and $Y_{2,3}$, and from X_2 and Y_2 the transmission side (right side) surface pressure of MPP1 and illuminated side (left side) surface pressure of PM are obtained. In the same way, from X_3 and Y_3 the transmission side (right side) surface pressure of PM and illuminated side (left side) surface pressure of MPP2 are obtained.

Next, the sound field in Domain [IV] is analysed. The sound pressure on the transmission side (right side) surface of MPP2, p_{d4}, is expressed by a Helmholtz-Kirchhoff integral as follows:

$$p_{d4}(x,D_1+D_2) = \frac{i}{2}\int_{-\infty}^{\infty}\frac{\partial p_{d4}(x_0,D_1+D_2)}{\partial n}H_0^{(1)}(k_0|x-x_0|)dx_0 \quad (15)$$

The boundary condition on the surface is:

$$\frac{\partial p_{d4}(x_0,D_1+D_2)}{\partial n} = -\rho_0\omega^2 w_3(x_0) - iA_{m3}k_0\Delta P_3(x_0) \quad (16)$$

Here, $A_{m3}=\rho_0 c_0/Z_3$. From these equations, the sound pressure on the transmission side (right side) surface of MPP2 becomes:

$$p_{d4}(x,D_1+D_2) = -\frac{i}{2}\int_{-\infty}^{\infty}[\rho_0\omega^2 w_3(x_0) + iA_{m3}k_0\Delta P_3(x_0)]H_0^{(1)}(k_0|x-x_0|)dx_0 \quad (17)$$

The displacement of the sound induced vibration of MPP1, PM and MPP2, $w_{1,2,3}(x)$, are expressed with the unit responses of MPP1, PM and MPP2, $u_{1,2,3}(x)$, respectively.

$$w_1(x) = \int_{-\infty}^{\infty} [p_{d1}(\xi,0) - p_{d2}(\xi,0)] u_1(x-\xi) d\xi \tag{18}$$

$$w_2(x) = \int_{-\infty}^{\infty} [p_{d2}(\xi,D_1) - p_{d3}(\xi,D_1)] u_2(x-\xi) d\xi \tag{19}$$

$$w_3(x) = \int_{-\infty}^{\infty} [p_{d3}(\xi,D_1+D_2) - p_{d4}(\xi,D_1+D_2)] u_3(x-\xi) d\xi \tag{20}$$

The equations above can be solved by using the Fourier transform technique in the wavenumber space (k) (see, e.g., Ref [13]). Fourier transform and inverse transform are defined as follows:

$$F(k) = \frac{1}{2\pi} \int_{-\infty}^{\infty} f(x) e^{-ikx} dx \tag{21}$$

$$f(x) = \int_{-\infty}^{\infty} F(k) e^{ikx} dk \tag{22}$$

Solving these equations in the wavenumber space simultaneously, and taking the inverse transform, the final forms of the reflected and transmitted pressures are obtained as follows:

$$p_r(x,z) = [1 + (1/k_0 \cos\theta)\{i\rho_0\omega^2\Gamma_1(k_0\sin\theta) - k_0 A_{m1}\varepsilon_1(\alpha_1\Gamma_1(k_0\sin\theta) + \alpha_2\Gamma_2(k_0\sin\theta) + \alpha_3\Gamma_3(k_0\sin\theta) + \alpha_4)\}]e^{i[k_0 x\sin\theta - k_0 z\cos\theta]} \tag{23}$$

$$p_t(x,z) = [(1/k_0 \cos\theta)\{-i\rho_0\omega^2\Gamma_3(k_0\sin\theta) + k_0 A_{m3}\varepsilon_3(\gamma_1\Gamma_1(k_0\sin\theta) + \gamma_2\Gamma_2(k_0\sin\theta) + \gamma_3\Gamma_3(k_0\sin\theta) + \gamma_4)\}]e^{i[k_0 x\sin\theta - k_0 z\cos\theta]} \tag{24}$$

where $\Gamma_{1,2,3}$, ε, $\alpha_{1,2,3}$ and $\gamma_{1,2,3}$ are functions including many parameters including the specific impedances of MPP1, 2 and PM and the cavity depths etc., and expressed as follows:

$$\Gamma_1(k) = \frac{Q_1 J_2 + J_1 J_3}{Q_1 Q_3 - J_1 J_4}$$

$$\Gamma_2(k) = \frac{Q_2 L_2 + L_1 L_3}{Q_1 Q_2 - L_1 L_4}$$

$$\Gamma_3(k) = \frac{Q_3 N_2 + N_1 N_3}{Q_2 Q_3 - N_1 N_4}$$

$$Q_1 = (1-\Phi_2\beta_2)(1-\Phi_3\gamma_3) - \Phi_2\Phi_3\beta_3\gamma_2$$
$$Q_2 = (1-\Phi_1\alpha_1)(1-\Phi_3\gamma_3) - \Phi_1\Phi_3\alpha_3\gamma_1$$
$$Q_3 = (1-\Phi_1\alpha_1)(1-\Phi_2\beta_2) - \Phi_1\Phi_2\alpha_2\beta_1$$
$$J_1 = \Phi_1\Phi_2\alpha_2\beta_3 + \Phi_1\alpha_3(1-\Phi_2\beta_2)$$
$$J_2 = \Phi_1\Phi_2\alpha_2\beta_4 + \Phi_1\alpha_4(1-\Phi_2\beta_2)$$
$$J_3 = \Phi_2\Phi_3\beta_4\gamma_2 + \Phi_3\gamma_4(1-\Phi_2\beta_2)$$
$$J_4 = \Phi_2\Phi_3\beta_1\gamma_2 + \Phi_3\gamma_1(1-\Phi_2\beta_2)$$
$$L_1 = \Phi_2\Phi_3\beta_3\gamma_1 + \Phi_2\beta_1(1-\Phi_3\gamma_3)$$
$$L_2 = \Phi_2\Phi_3\beta_3\gamma_4 + \Phi_2\beta_4(1-\Phi_3\gamma_3)$$
$$L_3 = \Phi_1\Phi_3\alpha_3\gamma_4 + \Phi_1\alpha_4(1-\Phi_3\gamma_3)$$
$$L_4 = \Phi_1\Phi_3\alpha_3\gamma_2 + \Phi_1\alpha_2(1-\Phi_3\gamma_3)$$
$$N_1 = \Phi_1\Phi_3\alpha_2\gamma_1 + \Phi_3\gamma_2(1-\Phi_1\alpha_1)$$
$$N_2 = \Phi_1\Phi_3\alpha_4\gamma_1 + \Phi_3\gamma_4(1-\Phi_1\alpha_1)$$
$$N_3 = \Phi_1\Phi_2\alpha_4\beta_1 + \Phi_2\beta_4(1-\Phi_1\alpha_1)$$
$$N_4 = \Phi_1\Phi_2\alpha_3\beta_1 + \Phi_2\beta_3(1-\Phi_1\alpha_1)$$

$$\Phi_1 = 2\pi U_1(k)\varepsilon, \quad \Phi_2 = 2\pi U_2(k)\varepsilon, \quad \Phi_3 = 2\pi U_3(k)\varepsilon$$
$$\varepsilon = \frac{1}{F_1G_1H_1 - F_1G_6H_4 - F_4G_5H_1}$$
$$\alpha_1 = F_2G_1H_1 - F_2G_6H_4 - F_4G_2H_1$$
$$\alpha_2 = F_3G_1H_1 - F_3G_6H_4 + F_4G_3H_1 + F_4G_6H_2$$
$$\alpha_3 = F_4G_6H_3 - F_4G_4H_1$$
$$\alpha_4 = 2G_4H_1 - 2G_6H_4$$
$$\beta_1 = F_1G_2H_1 - F_2G_5H_1$$
$$\beta_2 = -F_1G_3H_1 - F_1G_6H_2 - F_3G_5H_1$$
$$\beta_3 = F_1G_4H_1 - F_1G_6H_3$$
$$\beta_4 = -2G_5H_1$$
$$\gamma_1 = F_2G_5H_4 - F_1G_2H_4$$
$$\gamma_2 = F_1G_1H_2 - F_4G_5H_2 + F_1G_3H_4 + F_3G_5H_4$$
$$\gamma_3 = F_1G_1H_3 - F_4G_5H_3 - F_1G_4H_4$$
$$\gamma_4 = 2G_5H_4$$

$$H_1 = 1 - \frac{\rho_0 c_0 E_2}{C_2 Z_3} + A_3$$

$$H_2 = \frac{2BE_3}{C_2}, \quad H_3 = A_1 - \frac{BE_2}{C_2}, \quad H_4 = \frac{2\rho_0 c_0 E_3}{C_2 Z_2}$$

$$G_1 = 1 - \frac{\rho_0 c_0 E_1}{C_1 Z_2} - \frac{\rho_0 c_0 E_2}{C_2 Z_2}, \quad G_2 = \frac{2B}{C_1}, \quad G_3 = \frac{BE_1}{C_1} + \frac{BE_2}{C_2}$$

$$G_4 = \frac{2BE_3}{C_2}, \quad G_5 = \frac{2\rho_0 c_0}{C_1 Z_1}, \quad G_6 = \frac{2\rho_0 c_0 E_3}{C_2 Z_3}$$

$$F_1 = 1 + A_2 - \frac{\rho_0 c_0 E_1}{C_1 Z_1}$$

$$F_2 = A_1 - \frac{BE_1}{C_1}, \quad F_3 = \frac{2B}{C_1}, \quad F_4 = \frac{2\rho_0 c_0}{C_1 Z_2}$$

$$E_1 = e^{i\phi} + e^{-i\phi}, \quad E_2 = e^{2i\phi} + e^{2i\sigma}, \quad E_3 = e^{i(\phi+\sigma)}$$

$$C_1 = (e^{i\phi} - e^{-i\phi})\cos\theta, \quad C_2 = (e^{2i\sigma} - e^{2i\phi})\cos\theta$$

$$B = i\rho_0 c_0 \omega,$$

$$A_1 = \frac{i\rho_0 \omega^2}{\sqrt{k_0{}^2 - k^2}}, \quad A_2 = \frac{k_0 A_{m1}}{\sqrt{k_0{}^2 - k^2}}, \quad A_3 = \frac{k_0 A_{m3}}{\sqrt{k_0{}^2 - k^2}}$$

$$\varphi = k_0 D_1 \cos\theta, \qquad \sigma = k_0 (D_1 + D_2)\cos\theta$$

where, $U_{1,2,3}(k)$ is the Fourier transform of $u_{1,2,3}(x)$, and expressed in eqs. (25)…(27). $U_1(k)$ is the transformed unit response of MPP1， $U_2(k)$ is that of PM， $U_3(k)$ is that of MPP2.

$$U_1(k) = \frac{1}{2\pi(D_1 k^4 - \rho_1 t_1 \omega^2)}\,; D_{\mathrm{MPP1}} = \frac{E_{\mathrm{MPP1}} t_1{}^3 (1 - i\eta_{\mathrm{MPP1}})}{12(1-\nu_1^2)} \tag{25}$$

$$U_2(k) = \frac{1}{2\pi(Tk^2 - M\omega^2)} \tag{26}$$

$$U_3(k) = \frac{1}{2\pi(D_{\mathrm{MPP2}} k^4 - \rho_2 t_2 \omega^2)}\,; D_{\mathrm{MPP2}} = \frac{E_{\mathrm{MPP2}} t_2{}^3 (1 - i\eta_{\mathrm{MPP2}})}{12(1-\nu_2^2)} \tag{27}$$

and $\rho_{1,2}$, $E_{\mathrm{MPP1,2}}$, $\eta_{\mathrm{MPP1,2}}$, $\nu_{1,2}$ and $D_{\mathrm{MPP1,2}}$ are respectively, the densities, the Young's moduli, the loss factors, the Poisson's ratios and the flexural rigidity of MPP 1 and 2.

Regarding the tension T, the tension of PM, it is known in the previous studies that the tension affects the acoustic properties only when it is very large in the case of infinite extent as long as a usual building purpose membrane is considered. Besides, when a membrane is used an interior material, the tension does not become so large in actual situations. Therefore, in this study, the effect of the tension is neglected and T=0 is assumed in the following calculations.

Now, the absorption coefficient is obtained from the reflected pressure as:

$$\alpha_\theta = 1 - |p_r|^2 \tag{28}$$

The transmission coefficient is obtained from the transmitted pressure as:

$$\tau_\theta = |p_t|^2 \tag{29}$$

Considering the diffuse sound incidence, an average from 0 to 90 degrees of the angle of incidence, random incidence averaged value, is taken. Random incidence averaged absorption and transmission coefficients α and τ are obtained as follows:

$$\alpha = \frac{\int_{0^\circ}^{90^\circ} \alpha_\theta \sin\theta \cos\theta d\theta}{\int_{0^\circ}^{90^\circ} \sin\theta \cos\theta d\theta} \tag{30}$$

$$\tau = \frac{\int_{0^\circ}^{90^\circ} \tau_\theta \sin\theta \cos\theta d\theta}{\int_{0^\circ}^{90^\circ} \sin\theta \cos\theta d\theta} \tag{31}$$

For the diffuse sound field incidence, the field-incidence-averaged coefficients, which average from 0 to 78 degrees, are often used. However, a space absorber, such as a panel-like one which we consider here, sound incidence near 90 degrees can need to be taken into account. Therefore, averaging from 0 to 90 degrees is more reasonable in this case.

Also, one should note that the space absorber can transmit the sound energy, and the transmitted energy remains in the room. Therefore, to evaluate the sound energy actually dissipated in the absorber should be evaluated. Therefore, the difference between the absorption and transmission coefficients, $\alpha - \tau$, is used to evaluate the sound absorption performance in this study.

3. Numerical examples and discussion

In this section the sound absorption characteristics of the M-P-M absorber is discussed through theoretically calculated numerical examples. The results are compared with those of DLMPP and triple-leaf MPP space sound absorber (TLMPP [14]) for detailed discussion.

3.1 General discussions

General features of the sound absorption characteristics of an M-P-M absorber are summarised here. The sound absorbing structures compared for discussion are shown in Fig. 2. A typical example of the calculated results is shown in Fig. 3. The parameters in this example are typical for an MPP and PM: MPP's thicknesses (t) are 0.2 mm, hole diameters (d) are 0.2 mm and perforation ratios (p) are 0.8 %. PM's flow resistance (R) is 816 Pa s/m and surface density (M_{PM}) is 1.0kg/m^2. The cavity depths are D_1 between MPP1 and PM, D_2 between PM and MPP2, and both are 25 mm. The MPP's mechanical parameters are: densities (ρ) 7874 kg/m^3, Young's moduli (E) 205×10^9 Pa, loss factors (η_{MPP}) 0.0001 and Poisson's ratios (ν) 0.3 are assumed for both MPP1 and 2.

The absorption characteristics of M-P-M absorber, as observed in Fig. 3, have a resonance peak in mid to high frequency range. The characteristics are qualitatively similar to those of a DLMPP and TLMPP, which will be discussed in detail later. Since M-P-M absorber is a space absorber with acoustic permeability, its $\alpha - \tau$ shows almost constant value around 0.3…0.5 at low to mid frequencies (31.5…500 Hz). The value increases with increasing frequency. At mid to high frequencies it shows a single peak of around 0.7. at around 2 kHz. M-P-M absorber is a triple-leaf structure, but there is only one peak. This is because the PM added in the cavity does not form an additional resonator. This point will be discussed later in detail in Sec. 3.2. Above the peak resonance frequency the value becomes lower. There is a small peak at 8 kHz, which is assumed to be attributed to the higher resonance of the air cavity, which is not significant in absorption performance.

M-P-M absorber is now compared with a DLMPP (Fig. 2 (2-b)). Comparing the two curves, it is observed that they are qualitatively very similar. Especially, at low frequencies (31.5…250 Hz) they are almost the same. At mid and high frequencies, the peak appears at almost the same frequency, but the peak value is different: M-P-M absorber shows higher than DLMPP by 0.1 ca. Due to this difference, above 250 Hz, M-P-M absorber shows in general higher value than DLMPP. The difference between M-P-M absorber and DLMPP is only the PM in the air cavity, therefore, this acoustical difference is considered to be caused only by the PM in the cavity.

M-P-M absorber is now compared with TLMPP (Fig. 2 (2-c)). As observed in Fig. 3, they show a similar feature, as in the case of the comparison with DLMPP. At low frequencies (31.5…250 Hz) TLMPP shows higher value than M-P-M absorber. This is because the surface density of the PM in M-P-M absorber is smaller than that of the MPP in TLMPP: the absorptivity of a permeable material in general becomes lower with decreasing the surface density. Although the result is not shown here, we have checked that if the PM is heavier, this difference at low frequencies does not appear. Above 250 Hz both the M-P-M absorber and TLMPP show a resonance peak at around 2 kHz, but regarding the value M-P-M absorber is higher than TLMPP.

From the discussion above, as for the resonance peak M-P-M absorber shows higher value than DLMPP and TLMPP, which is to say that the sound absorption performance is improved by the PM in the cavity. However, this advantage is rather limited at and around the resonance peak: the performance is not much different at other frequencies.

3.2 Effect of honeycomb in the cavity on M-P-M absorber

In the previous studies, it is proved that a honeycomb in the air cavity is effective not only for reinforcing the structure but also improving the sound absorption performance [15, 16]. Therefore, it is expected that a honeycomb can improve the absorption performance of an M-P-M absorber. The effect of a honeycomb in the air cavity on an M-P-M absorber is discussed through theoretically calculated results. The model of an M-P-M absorber with a honeycomb is shown Fig. 4.

The calculated results are shown in Fig. 5. The cases with a honeycomb in one cavity only (Fig. 4 (4-b) and (4-c)) are considered as the same condition because the M-P-M absorber is a space absorber: therefore, the results are taken as the average of $\alpha - \tau$ for the incidence from right and left sides.

First, the case without honeycomb (Fig. 4 (4-a)) is compared with the case with a honeycomb in one cavity (Fig. 4 (4-b) and (4-c)). From Fig. 5, the absorptivity of the case with a honeycomb becomes slightly higher than that without a honeycomb at 31.5…100 Hz. There is not much difference at 100…125 Hz, but the difference becomes larger above 125 Hz. The peak is caused at around 1.5 kHz in the case with a honeycomb in one cavity, and the peak value becomes higher by 0.1 than that without a honeycomb.

Next the case without honeycomb is compared with the case with honeycombs in both cavities (Fig. 4 (4-d)). From Fig. 5, there is no significant difference at 31.5…125 Hz. Above 125 Hz, M-P-M absorber with honeycomb in the both cavities show higher value. The peak is caused around 1.5 kHz, which is the same as the case with a honeycomb in one cavity, and the peak value is higher by 0.2 than that without a honeycomb. There is a very sharp peak at high frequencies, which is attributed to the higher resonance of the cavity: this appears because the sound field in the cavity becomes that in the case of normal incidence due to the honeycomb.

From the above discussion, both in the cases of a honeycomb in one cavity and honeycombs in both cavities show better sound absorption performance. Particularly, the case of honeycombs in both cavities shows greater improvement. As in the previous studies, the resonance peak shifts to lower frequencies, and the absorptivity becomes higher at mid and high frequencies owing to the effect of the honeycomb. Thus, a honeycomb is also effective for the M-P-M absorber.

4. Concluding remarks

In this paper the sound absorption characteristics of a double-leaf MPP space sound absorber (DLMPP) with a permeable membrane (PM) in its air cavity (M-P-M absorber). As the result, the PM is efficient to improve the absorptivity of a DLMPP: the resonance peak absorption becomes higher and more significant by the effect of the PM. The M-P-M absorber is proved that it can offer better sound absorption performance than DLMPP and TLMPP (triple-leaf MPP space sound absorber). This means that the M-P-M absorber is much better than TLMPP in both acoustic and cost considerations. Also, as the PM is not very expensive, adding a PM in a DLMPP can be a good alternative to produce a better sound absorber.

The effect of a honeycomb in the air cavity of the M-P-M absorber is also theoretically investigated. The results show that the honeycomb makes the sound absorption performance of the M-P-M absorber significantly, especially when the honeycombs are inserted in the both air cavities of the M-P-M absorber.

From the above investigation, the PM is also effective to improve the sound absorption performance of not only the common MPP absorbers with backing structure [15], but also the MPP space absorber such as DLMPP. The M-P-M absorber will be one of effective alternatives in this type of MPP space sound absorbers.

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Captions of figures

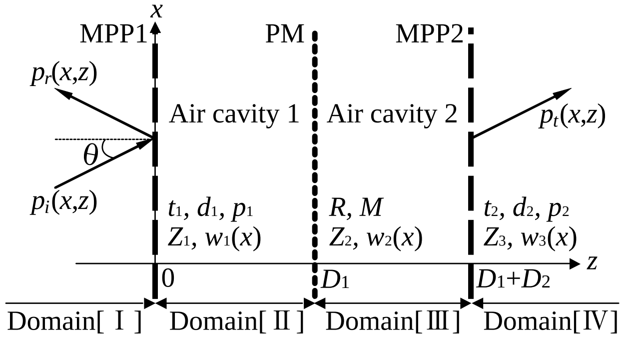
Fig. 1. Model for analysis of a triple-leaf sound absorbing structure with double-leaf MPP space absorber with a permeable membrane in the air cavity (M-P-M absorber).

Fig. 2. Sound absorbing structures to be compared with the M-P-M absorber. 2-a: M-P-M absorber, 2-b: DLMPP (double-leaf MPP space sound absorber), and 2-c: TLMPP (triple-leaf MPP space sound absorber).

Fig. 3. Calculated example of the sound absorption characteristics (random incidence) when the sound is incident from the MPP side. Thick line: M-P-M absorber, Thin line: DLMPP, Dashed line: TLMPP. Parameters of all MPPs : t=0.2mm, d=0.2mm, p=0.8%, ρ=7874 kg/m^3, E= 205$\times$10^9 Pa, η_{MPP}= 0.0001, ν= 0.3. Parameters of all PMs : R=816Pa s/m, M_{PM}=1.0kg/m^2, D_1=D_2=25mm

Fig. 4. The model of the M-P-M absorbers with a honeycomb in the cavity. 4-a: M-P-M absorber without honeycomb, 4-b: with honeycomb in the air cavity 1 only, 4-c: with honeycomb in the air cavity 2 only, and 4-d: with honeycombs in the both cavities.

Fig. 5. The effect of honeycomb on the sound absorption characteristics of M-P-M absorber. Thick line: with honeycombs in both the cavites (4-d), Thin line: without honeycomb (4-a), and Dotted line: with honeycomb in one cavity only (average of 4-b and 4-c).



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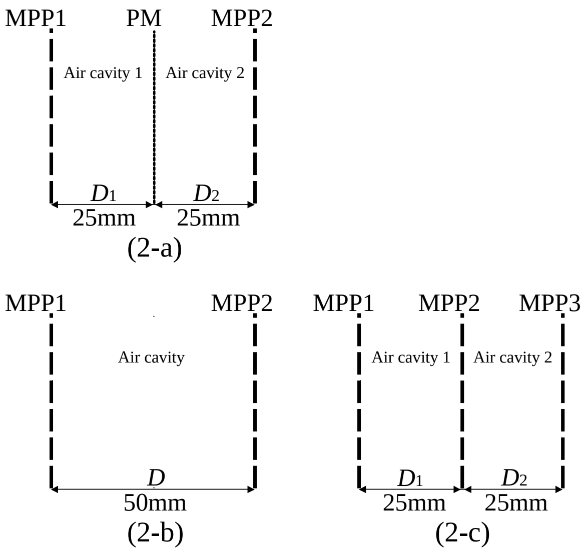

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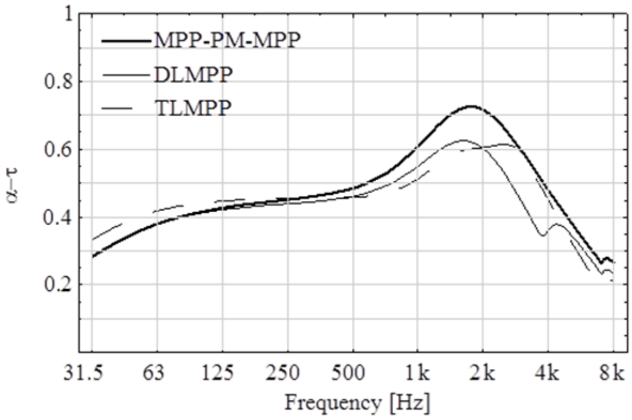

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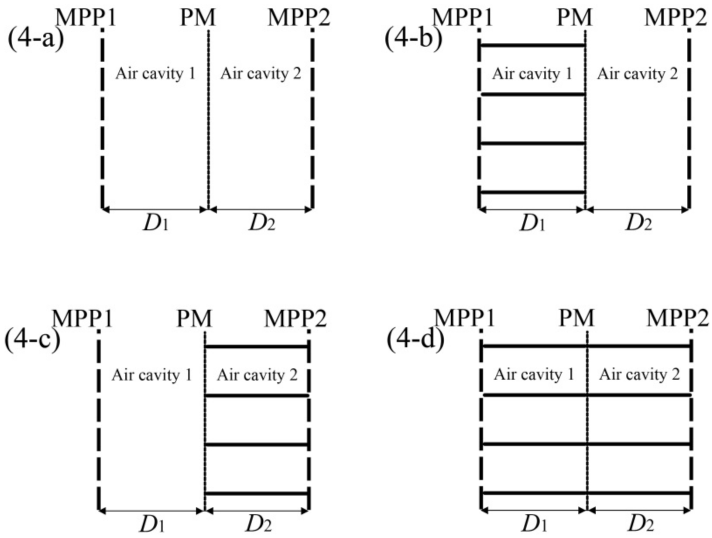

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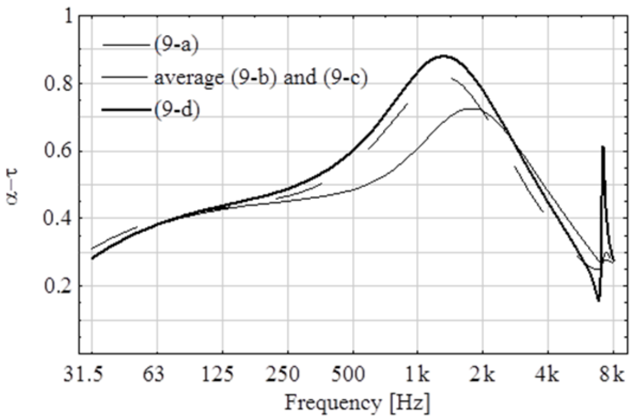

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