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Effect of a honeycomb on the absorption characteristics of double-leaf microperforated panel (MPP) space sound absorbers

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ABSTRACT

Sound absorbers using a microperforated panel (MPP) is usually not strong enough for room interior surfaces because MPPs are in general very thin. In order to solve this weakness, the authors proposed to use a honeycomb attached behind an MPP in the air-back cavity. In the authors previous studies a honeycomb is effective to improve the sound absorption performance of an ordinary wall-backed single-leaf MPP sound absorber. The honeycomb can also be applied to a space sound absorbing structures such as a double-leaf MPP space absorber (DLMPP). In this study, the effect of a honeycomb in the air-cavity on the sound absorption characteristics of a DLMPP is theoretically analysed. In the theory a Helmholtz-Kirchhoff integral formulation is utilised. The theory is validated with experimental results. The effect of the honeycomb on the sound absorption characteristics is discussed through the numerical examples calculated by the present theory. The results show that the honeycomb enhances the resonance peak and shifts it to lower freqeuencies. Although the honeycomb is effective to improve the sound absorption performance of a DLMPP at around resonance peak, it does not affect the additional low frequency absorption which is particular to a DLMPP.

1. INTRODUCTION

Microperforated panels (MPPs) are thin panels or films of arbitrary material, ie, metal or plastics, with submillimetre perforations (diameter < 1 mm, perforation ratio < 1%) [1-4]. They are more durable than traditional common sound absorbing materials: MPPs can be usable in severe environment. Also they are more designable than the most of the other sound absorbing materials. With these attractive features, MPPs have therefore become widely known and various applications have been attempted recently. MPPs are usually placed in parallel to a rigid-back wall with an air-cavity in-between, so that a Helmholtz-type resonance absorber composed of the perforations with the air-cavity is formed. This results in high absorptivity in selected but relatively wide frequency range (comparing with other resonance type absorbers) at mid- to high-frequencies.

However, in an MPP sound absorbing structure, because an MPP is very thin, it is not strong enough to use as an interior surface in buildings: it must be reinforced by some supporting structures. One of the means to support the MPP, a honeycomb structure is proposed to be attached behind it. The acoustical effect of the honeycomb on the sound absorbing performance of an MPP sound absorber has been studied by the authors [5-9]. In these studies the sound absorption characteristics of a single-leaf and double-leaf MPP sound absorbing structure with a rigid-back wall were analysed by wave theory using a Helmholtz-Kirchhoff integral formulation. Also, a honeycomb can be used for a double-leaf MPP space sound absorber (DLMPP) without back wall [10,11] and a similar effect can be expected, however, this has not yet been studied.

In the present paper, a DLMPP with a honeycomb in its air-cavity is proposed and its sound absorption characteristics are analysed by wave acoustic theory using a Helmholtz-Kirchhoff integral formulation. The theory is based on that for a DLMPP without a honeycomb [11], but some modifications to include the acoustical effect of subdividing the air-cavity by a honeycomb are made for the present purpose. The theory is validated with experimental results. Numerical examples calculated by the theory are presented, through which the effect of the MPP parameters (hole diameter, thickness, perforation ratio etc) and the honeycomb thickness on the sound absorption characteristics are discussed in detail.

2. THEORETICAL CONSIDERATIONS

Figure 1 shows the model for the theoretical analysis of a DLMPP. The DLMPP is in x-y plane, and is of infinite extent. In this analysis, it is assumed that the honeycomb has only an acoustical effect: it does not exert a force to the leaves, and have no mechanical effect. This is to concentrate on the acoustical effect of the honeycomb, i.e., the effect of subdivision of the cavity. A plane sound wave of unit pressure amplitude is incident upon it with an angle of incidence θ, therefore the sound field becomes two-dimensional. MPP1 and MPP2 have the following parameters, respectively: the thicknesses, $t_{1,2}$; the hole diameters, $d_{1,2}$; the perforation ratios, $p_{1,2}$; the surface density, $M_{1,2}$ (average over the unit area including the holes), and the specific acoustic impedances, $Z_{1,2}$ (for unit area). The depth of the air cavity is D. The vibration displacements of the MPP1 and MPP2 are $w_{1,2}(x)$, respectively. The time factor $\exp(-i\omega t)$ is suppressed throughout. For the specific acoustic impedances of the MPPs, $Z_{1,2}$, in this study the formulae proposed by Maa [2] which showed the best agreement with our experimental data (detailed later) are used. It is expressed, being the specific acoustic resistance $r_{1,2}$ and reactance $\omega m_{1,2}$, as follows (note that all impedances are normalised by the air impedance $\rho_0 c_0$ hereafter):

$$Z_{1,2} = r_{1,2} - i\omega m_{1,2} \tag{1}$$

where

$$r_{1,2} = \frac{32\eta t_{1,2}}{p_{1,2}\rho_0 c_0 d_{1,2}^{\ 2}}\left(\sqrt{1+\frac{k_{1,2}^{\ 2}}{32}} + \frac{\sqrt{2}}{8}k_{1,2}\frac{d_{1,2}}{t_{1,2}}\right) \tag{2}$$

$$\omega m_{1,2} = \frac{\omega t_{1,2}}{p_{1,2}c_0}\left(1 + \frac{1}{\sqrt{9+\frac{k_{1,2}^{\ 2}}{2}}} + 0.85\frac{d_{1,2}}{t_{1,2}}\right) \tag{3}$$

$$k_{1,2} = d_{1,2}\sqrt{\frac{\omega\rho_0}{4\eta}} \tag{4}$$

Here, ρ_0 is the air density, c_0 is the sound speed in air, ω is the angular frequency (=$2\pi f$, f: frequency), η is the dynamic viscosity of the air (=1.789*10^{-5} [Pa s]).

The surface sound pressure on the illuminated side of the MPP1, $p_1(x,0)$, is expressed by using a Helmholtz-Kirchhoff integral formula, as follows:

$$p_1(x,0) = 2p_i(x,0) + \frac{i}{2}\int_{-\infty}^{\infty}\frac{\partial p_1(r_0,0)}{\partial n}\mathrm{H}_0^{(1)}(k_0|x-x_0|)dx_0 \tag{5}$$

where, p_i is the pressure of the incident wave, n is the outward normal vector, and $\mathrm{H}_0^{(1)}$ is the first kind Hankel function of order zero. The boundary condition of the surface of the illuminated side of MPP1 is

$$\frac{\partial p_1(x_0,0)}{\partial n} = \rho_0\omega^2 w\ (x) + ik_0 A_{m1}\Delta p_1(x_0) \tag{6}$$

where, Δp_1 is the pressure difference between the two surfaces of MPP1, $A_{\mathrm{m}1}=\rho_0 c_0/Z_1$, and k_0 is the wavenumber in the air. From these equations, the sound pressure on the illuminated side surface of MPP1, $p_1(x,0)$, is

$$p_1(x,0) = 2p_i(x,0) + \frac{i}{2}\int_{-\infty}^{\infty}[\rho_0\omega^2 w_1(x_0) + iA_{m1}k_0\Delta p_1(x_0)]H_0^{(1)}(k_0|x-x_0|)dx_0 \tag{7}$$

The sound pressure and the particle velocity in the air cavity are expressed as:

$$p_2(x,z) = (Xe^{ik_0 z\cos\theta} + Ye^{-ik_0 z\cos\theta})e^{ik_0 x\sin\theta} \tag{8}$$

$$v_2(x,z) = \frac{\cos\theta}{\rho_0 c_0}(Xe^{ik_0 z\cos\theta} - Ye^{-ik_0 z\cos\theta})e^{ik_0 x\sin\theta} \tag{9}$$

where, X and Y are the pressure amplitudes of the waves in the air cavity propagating in +z and –z directions, respectively. When the air-cavity is filled with a honeycomb, the sound wave is forced to travel nearly normal to the MPPs in the honeycomb cells (ie, +/-z direction, which is to say θ=0). Therefore, in that case, θ=0 is substituted in Eqs (8) and (9) so that $\cos\theta$ becomes 1. The boundary conditions in the air layer (including the honeycomb filled case) are expressed as:

$$v_1(x,0) = -i\omega w_1(x) + \frac{\Delta p_1(x)}{Z_1} \tag{10}$$

$$v_2(x,D) = -i\omega w_2(x) + \frac{\Delta p_2(x)}{Z_2} \tag{11}$$

From Eqs (8)-(11) the complex pressure amplitudes X and Y are obtained. From X and Y the pressure on the transmitted side (back side) surface of MPP1 and the front side (cavity side) surface of MPP2 are given.

The sound pressure on the transmitted side (back side) of MPP2, $p_3(x,D)$, is expressed as follows by using a Helmholtz-Kirchhoff integral formula:

$$p_3(x,D) = \frac{i}{2}\int_{-\infty}^{\infty} \frac{\partial p_3(r_0,0)}{\partial n} H_0^{(1)}(k_0|x-x_0|)dx_0 \tag{12}$$

Similar procedure as to derive Eq (6) can be applied and the following relationship is given:

$$\frac{\partial p_3(x_0,D)}{\partial n} = -\rho_0\omega^2 w_2(x) + ik_0 A_{m2}\Delta p_2(x_0) \tag{13}$$

where, Δp_2 is the difference of sound pressure on the two sides of MPP2, and $A_{m2}=\rho_0 c_0/Z_2$. From these equations the sound pressure on the surface of the transmitted side of MPP2, $p_3(x,D)$ is obtained as follows:

$$p_3(x,D) = -\frac{i}{2}\int_{-\infty}^{\infty} [\rho_0\omega^2 w_2(x_0) - iA_{m2}k_0\Delta p_2(x_0)]H_0^{(1)}(k_0|x-x_0|)dx_0 \tag{14}$$

The vibration displacements of MPP1 and MPP2, $w_{1,2}(x)$, are expressed by using their unit responses $u_{1,2}(x)$ as follows:

$$w_1(x) = \int_{-\infty}^{\infty} [p_1(\xi,0) - p_2(\xi,0)]u_1(x-\xi)d\xi \tag{15}$$

$$w_2(x) = \int_{-\infty}^{\infty} [p_2(\xi,D) - p_3(\xi,D)]u_2(x-\xi)d\xi \tag{16}$$

The above all equations are solved simultaneously by using the Fourier transform technique. The Fourier transform and the inverse transform are defined as follows:

$$F(k) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(x)e^{-ikx}dx \tag{17}$$

$$f(x) = \int_{-\infty}^{\infty} F(k)e^{ikx}dk \tag{18}$$

In the above procedure the transform of the unit responses $u_{1,2}(x)$, $U_{1,2}(k)$ are expressed, according to the thin panel theory, as follows:

$$U_{1,2}(k) = \frac{1}{2\pi(D_{1,2}k^4 - \rho_{1,2}t_{1,2}\omega^2)} \tag{19}$$

where

$$D_{1,2}(k) = \frac{E_{1,2}t_{1,2}{}^3(1 - i\eta_{p1,2})}{12(1 - \upsilon_{1,2}{}^2)} \tag{20}$$

where, $E_{1,2}$, $\eta_{p1,2}$, $\rho_{1,2}$, $\upsilon_{1,2}$, $D_{1,2}$ are the Young's moduli, loss factors, densities, Poisson's ratios and flexural rigidity of MPP1 and MPP2, respectively. However, in many cases without a honeycomb, with the panels of infinite extent, the effect of the flexural rigidity is known to be negligibly small [12]. It may be significant when the mechanical effect on the sound induced vibration on MPPs is included, however, it is not taken into account in this study. Therefore in this study it will be neglected hereafter, and the transforms of the unit responses of MPP1 and MPP2 are used in the following simplified form:

$$U_{1,2}(k) = \frac{1}{2\pi(-M_{1,2}\omega^2)} \tag{21}$$

From the above the reflected and transmitted pressures, p_r and p_t, are derived as follows:

$$p_r(x,z) = \left[1 + \frac{i\rho_0\omega^2\Gamma_1(k_0\sin\theta) - k_0A_{m1}\{A_1\Gamma_1(k_0\sin\theta) + A_2\Gamma_2(k_0\sin\theta) + A_3\}}{k_0\cos\theta}\right]\exp[\ i(k_0\sin\theta\, x - k_0\cos\theta\, z)] \tag{22}$$

$$p_t(x,z) = \left[\frac{-i\rho_0\omega^2\Gamma_2(k_0\sin\theta) + k_0A_{m2}\{B_1\Gamma_1(k_0\sin\theta) + B_2\Gamma_2(k_0\sin\theta) + B_3\}}{k_0\cos\theta}\right]\exp[\ i(k_0\sin\theta\, x - k_0\cos\theta\, z)] \tag{23}$$

where, $\Gamma_{1,2}$, $A_{1,2,3}$, $B_{1,2,3}$ are fairly complex functions including MPPs' impedances and cavity depth etc, and expressed as follows:

$$\Gamma_1 = Q_1(N_3 + \frac{N_2Q_3}{Q_2}),\quad \Gamma_2 = \frac{Q_3}{Q_2}$$

$$A_1 = N_1,\quad A_2 = N_2,\quad A_3 = N_3$$

$$B_1 = \frac{L_2}{L_1},\quad B_2 = \frac{L_3}{L_1},\quad B_3 = 2L_3$$

$$C_1 = \frac{\rho_0c_0}{\cos\theta},\quad C_2 = \frac{C_1}{\exp[i\varphi] - \exp[-i\varphi]}$$

$$F_1 = i\omega,\quad F_2 = C_1 + C_2\exp[-i\varphi]$$

$$G_1 = C_1\exp[-i\varphi] + F_2,\quad G_2 = C_2 + F_2\exp[-i\varphi],\quad G_3 = C_2(\exp[i\varphi] + \exp[-i\varphi])$$

$$H_1 = 1 + M_1 - \frac{G_1}{Z_1}, \quad H_2 = Z - F_1 G_1, \quad H_3 = \frac{G_2}{H_1 Z_1}$$

$$L_1 = 1 + M_2 - \frac{G_3}{Z_2} - \frac{2C_2 H_3}{Z_2}, \quad L_2 = F_1 G_2 - H_2 H_3, \quad L_3 = Z - F_1 G_3 - 2C_2 F_1 H_3, \quad L_4 = \frac{2C_2}{L_1 Z_2}$$

$$N_1 = \frac{H_2 - L_2 L_4}{H_1}, \quad N_2 = \frac{2C_2 F_1 - L_3 L_4}{H_1}, \quad N_3 = \frac{2(1 + H_3 L_4)}{H_1}$$

$$Q_1 = \frac{1}{2\pi U_1 - N_1}, \quad Q_2 = \frac{1}{2\pi U_2} - \frac{L_3}{L_1} - \frac{L_2 N_2 Q_1}{H_1}, \quad Q_3 = \frac{L_2 N_3 Q_1 - 2H_3}{L_1}$$

$$M_1 = \frac{k_0 A_{m1}}{k_0 \cos\theta}, \quad M_2 = \frac{k_0 A_{m2}}{k_0 \cos\theta}$$

$$Z = \frac{i\rho_0 \omega^2}{k_0 \cos\theta}, \quad \varphi = k_0 D \cos\theta$$

From the above solutions, the (oblique incidence) sound absorption coefficient α_θ=1-$|p_\mathrm{r}|^2$, and the transmission coefficient τ_θ=$|p_\mathrm{t}|^2$ are obtained. Since a DLMPP is a space absorber, the sound cannot only be absorbed but also transmitted through it. Therefore, it is needed to evaluate the energy that is actually dissipated in the structure. For this reason, in order to evaluate the sound absorption performance of a DLMPP, the difference of the absorption and transmission coefficients, α_θ-τ_θ, which describes the ratio of the energy dissipated in the structure. In the discussion later this difference α_θ-τ_θ is averaged from 0 to 78 degrees of the angle of incidence in the half space as in the following equation to obtain the field-incidence-averaged value:

$$\alpha - \tau = \frac{\int_{0^\circ}^{78^\circ} (\alpha_\theta - \tau_\theta) \sin\theta \cos\theta d\theta}{\int_{0^\circ}^{78^\circ} \sin\theta \cos\theta d\theta} \tag{24}$$

3. RESULTS AND DISCUSSION

3.1 Experimental validation

In this section the sound absorption characteristics of a DLMPP with honeycomb are calculated by the present wave theory. The numerical results are validated with experimental results.

The MPPs used in the experiments are two kinds: one is designed and made for acoustical purposes which are acoustically optimised. The other is made for non-acoustical purpose which is not acoustically designed and not optimised. For these two types of MPPs, DLMPP specimens were made and their sound absorption coefficients were measured, in accordance with JIS A 1409 (ISO compatible) except for the placement of the specimens: the specimens were placed vertically to the floor. The reverberation chamber is of volume 513 m^3 and surface area 382 m^2. Note that, the diffuse sound field absorption coefficient measured in a reverberation chamber corresponds to the average of the theoretical values of $\alpha-\tau$ for the sound incidences from the front and from the back [13]. Therefore, the theoretical values of the average of $\alpha-\tau$ for the incidence from front and for that from the back are calculated for the comparison.

The parameters of the specimens are presented in Table 1. The cavity depths are kept constant at

150 mm in all specimens. Here, the theoretical results for specimens A, B, C and D are compared with the experimental results in Fig. 2 (a) – (d).

In Fig. 2, the discrepancies between theoretical and experimental values becomes fairly large at the frequencies where the absorption coefficient is high by the resonance peak. This is inferred to be attributed as the area effect appearing more significant where the absorption coefficient becomes high. Therefore, in specimens A and C which show generally high absorption at all frequencies, including the Helmholtz resonance peak and the sharp peak by higher order resonance of the air cavity, the discrepancies are relatively large.

However, in all specimens some discrepancies are found around the resonance peak frequencies though, in other frequency range the theoretical values express somewhat well the measured sound absorption characteristics of a DLMPP. Therefore, though some discrepancies are observed, the present theory can be useful to study qualitatively the sound absorption characteristics of a DLMPP.

3.2 The acoustical effect of the honeycomb

In the previous studies [5-9] it is found that the honeycomb has no acoustical effect on the sound absorption of DLMPP absorbers in the case of normal incidence. Knowing this fact, in this study also it is checked if the honeycomb affects the characteristics in the normal incidence case, and we obtained the results supporting the previous studies. Therefore, only oblique and field-incidence averaged characteristics are studied hereafter. To concentrate on the honeycomb's effect in the following calculation MPP's sound induced vibration is neglected.

Figure 3 shows the theoretical results of the absorption characteristics for oblique incidence (the angles of incidence: 30 and 60 degrees) of a DLMPP. Adding the honeycomb in the cavity, the peak frequency shifts to lower frequencies, and the peak value becomes larger. However, in the case of the angle of incidence 30 degree the effect of the honeycomb on the absorption characteristics is rather smaller, but in the case of 60 degrees it is larger: the characteristics significantly change by the honeycomb. In general, with increasing the angle of incidence, the peak shifts to high frequencies, and the peak value decreases. But, when a honeycomb is attached, this tendency does not appear significantly, and the dependence on the angle of incidence changes.

For discussing the effect of the MPP parameters on the angle dependence, similar calculations were also made for different MPP parameters (Fig. 4). In Fig. 4 (a), the peak is maximised when the angle of incidence is 60 degrees. In Fig. 4 (b), the peak value is almost constant with the angle of incidence from 0 to 60 degrees. From these results, not only a honeycomb but the MPP parameters also affect the dependence on the angle of incidence.

Next, theoretical results for field-incidence-averaged absorption coefficients are shown in Fig. 5.

In Fig. 5, the effect of the honeycomb appears as to shift the peak to lower frequencies and to increase the peak absorption coefficient, which is similar to the oblique incidence cases. When a honeycomb is inserted, in the case of a single- and double-leaf MPP absorber (with a rigid-back wall), it is known that the absorptivity at low frequencies is greatly increased [8,9]. On the contrary, in the case of a DLMPP, there is no difference in absorption characteristics at low frequencies, especially below 125 Hz. This is explained as follows: in general honeycomb makes the characteristics similar to those for normal incidence, however, in the case of a DLMPP, at low frequencies, the dependence of the absorption characteristics on the angle of incidence is much less significant. Therefore, the absorptivity of a DLMPP at low frequencies is not raised even though a honeycomb is inserted in the cavity.

3.3 Effect of MPP parameters on the honeycomb effect

Here, in order to clarify the effect of MPP parameters (thickness, hole diameter, perforation ratio, and surface density) on the acoustic properties of a honeycomb-filled DLMPP, theoretical results for a honeycomb-filled DLMPP of various MPP parameters are compared with those with those for a DLMPP without honeycomb.

First, the thicknesses of the two MPPs in a honeycomb-filled DLMPP are changed from 0.1 mm to 0.8 mm. The results are shown in Fig. 6 (a) (with honeycomb) and (b) (without honeycomb). In these calculations the sound induced vibration of the leaves is neglected. Figure 6 (a) and (b) show that the peak frequency shifts to lower frequencies, and that the fluctuation of the absorption characteristics becomes less significant with increasing thickness of the MPPs. Comparing Figs. 6 (a) and (b), tendency of the change in frequency characteristics is considered to be similar to each other, however, the shift of the peak frequency is more significant in the case of a honeycomb-filled DLMPP.

Next, the hole diameters of the two MPPs in a honeycomb-filled DLMPP are changed from 0.1 mm to 0.8 mm. The results are shown in Fig. 7 (a) (with honeycomb) and (b) (without honeycomb). Again, in these calculations the sound induced vibration of the leaves is neglected. As is seen in Fig. 7 (a) and (b), within the range of the variation of hole diameter in this study, absorption performance deteriorates with increasing the hole diameter. However, the way in which the honeycomb affects the absorption characteristics does not change with hole diameter change.

Next, the perforation ratio of the two MPPs in a honeycomb-filled DLMPP are changed from 0.2% to 1.6%. The results are shown in Fig. 8 (a) (with honeycomb) and (b) (without honeycomb). Again, in these calculations the sound induced vibration of the leaves is neglected. Both in Fig. 8 (a) and (b) the peak frequency shifts to higher frequencies with increasing the perforation ratio. However, having a close look into the figures, the above tendency is more significant in the case of a honeycomb-filled DLMPP (a).

In the previous studies, in a DLMPP without honeycomb, the mass of MPP leaves has a somewhat large effect at low frequencies [11]. Therefore, next, the surface densities of the two MPPs in a honeycomb-filled DLMPP are changed from 0.1kg/m^2 to 3.0kg/m^2. The results are shown in Fig. 9 (a) (with honeycomb) and (b) (without honeycomb). Again, in these calculations the sound induced vibration of the leaves is neglected. The results show that the absorption characteristics drastically change at low frequencies with the surface density. When the surface density is extremely small, the low frequency absorption, which is one of the main features of a DLMPP, deteriorates. With attaching a honeycomb, the absorption performance around the resonance peak can be improved, but the above deterioration with small surface density at low frequencies cannot be improved.

4. CONCLUDING REMARKS

In this paper the sound absorption characteristics of a DLMPP (double-leaf MPP space sound absorber) with a honeycomb in its air-cavity are theoretically analysed, and discussed through numerical examples.

The theoretical solution was compared with experimental results: they show somewhat large discrepancies around the peak frequencies, but showed fairly good agreement in the other frequency range. Therefore, the theory can be useful to study qualitatively the absorption characteristics of a DLMPP with and without a honeycomb.

Numerical studies reveal that the following features of the absorption characteristics of a honeycomb-filled DLMPP: Due to the effect of the honeycomb the peak frequency shifts to lower frequencies and the peak value increases. In the previous studies on the existing MPP absorbing structures, i.e., single- and double-leaf MPP absorbers with a rigid-back wall, attaching honeycomb in the cavity makes the sound absorption performance, especially at low frequencies, improved. However, in the case of a DLMPP the low frequency absorptivity does not increase with honeycomb. The effect of a honeycomb is rather limited into the Helmholtz resonance peak frequency range.

Besides, honeycomb enhances the effect of the changes in MPP parameters on the sound absorption characteristics: i.e., the effect of the change in MPP parameters is more significant in the case of a honeycomb-filled DLMPP.

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Table 1. The parameters* of the specimens used in the experiments.

Specimen	MPP parameters			Honeycomb's thickness
	d	*t*	p	
A	0.5mm	0.5mm	0.64%	150mm
B	0.5mm	0.5mm	0.64%	0mm
C	0.2mm	0.2mm	0.785%	150mm
D	0.2mm	0.2mm	0.785%	0mm

*The surface densities of the MPPs are: 4kg m^{-2} in Specimens A and B, and 1.2kg m^{-2} in Specimens C and D.

Captions of figures

Fig.1. Geometry of a double-leaf microperforated panel space sound absorber (DLMPP) for theoretical analysis.

Fig. 2. Comparison of the calculated and measured sound absorption characteristics of DLMPPs with and without honeycomb. (a) Specimen A, (b) Specimen B, (c) Specimen C and (d) Specimen D. Solid line: calculated value by the present wave theory; Dots: measured values.

Fig. 3. The effect of a honeycomb in the cavity on the oblique incidence sound absorption characteristics of a DLMPP. The angle of incidence is (a) 30 degrees, and (b) 60 degrees. d = t =0.15mm, p=1%, D=50mm. Solid line: With honeycomb; Dashed line: Without honeycomb.

Fig. 4. The effect of the angle of incidence on the oblique incidence sound absorption characteristics of a honeycomb attached DLMPP. (a) d = t =0.15mm, p=1%, D=50mm, (b) d = t =0.5mm, p=0.64%, D=50mm. The angles of incidence are as follows: Solid line: Normal incidence; Dashed line: 30 degrees; Thin line: 60 degrees; Dotted line: 78 degrees.

Fig. 5. The effect of the honeycomb in the cavity on the field-incidence-averaged sound absorption characteristics of a DLMPP. d = t =0.15mm, p=1%, D=50mm. Solid line: With honeycomb; Dashed line: Without honeycomb.

Fig. 6. The effect of the thicknesses of the MPPs of a DLMPP. d =0.15mm, p=1%, D =50mm. (a) With honeycomb, and (b) without honeycomb. Solid line: t = 0.1mm; Dashed line: t = 0.2mm; Thin line: t = 0.4mm; Dotted line: t = 0.8mm.

Fig. 7. The effect of the hole diameters of the MPPs of a DLMPP. t =0.15mm, p=1%, D =50mm. (a) With honeycomb, and (b) without honeycomb. Solid line: d = 0.1mm; Dashed line: d = 0.2mm; Thin line: d = 0.4mm; Dotted line: d = 0.8mm.

Fig. 8. The effect of the perforation ratios of the MPPs of a DLMPP. d=t =0.15mm, D =50mm. (a) With honeycomb, and (b) without honeycomb. Solid line: p = 0.2%; Dashed line: p = 0.4%; Thin line: p = 0.8%; Dotted line: p = 1.6%.

Fig. 9. The effect of the surface densities of the MPPs of a DLMPP. d=t =0.15mm, p =0.1%, D =50mm. (a) With honeycomb, and (b) without honeycomb. Solid line: M= 3.0 kg/m^2; Dashed line: M= 1.0 kg/m^2; Thin line: M= 0.5 kg/m^2; Dotted line: M= 0.1 kg/m^2.

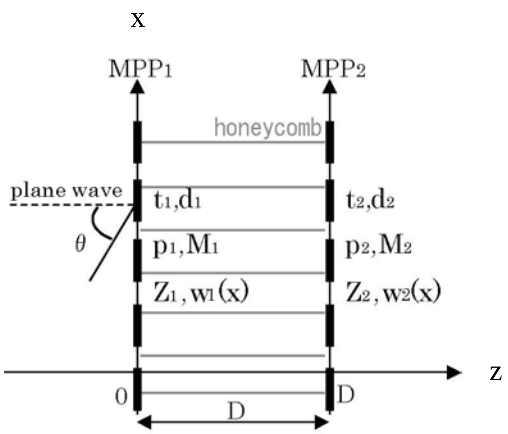

Fig.1. Geometry of a double-leaf microperforated panel space sound absorber (DLMPP) for theoretical analysis.

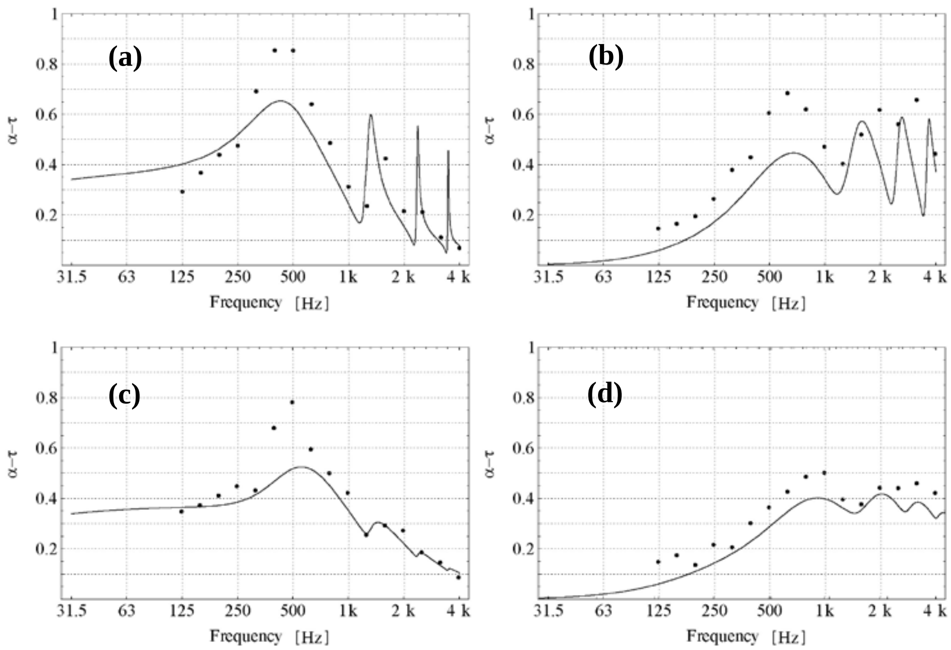

Fig. 2. Comparison of the calculated and measured sound absorption characteristics of DLMPPs with and without honeycomb. (a) Specimen A, (b) Specimen B, (c) Specimen C and (d) Specimen D. Solid line: calculated value by the present wave theory; Dots: measured values.

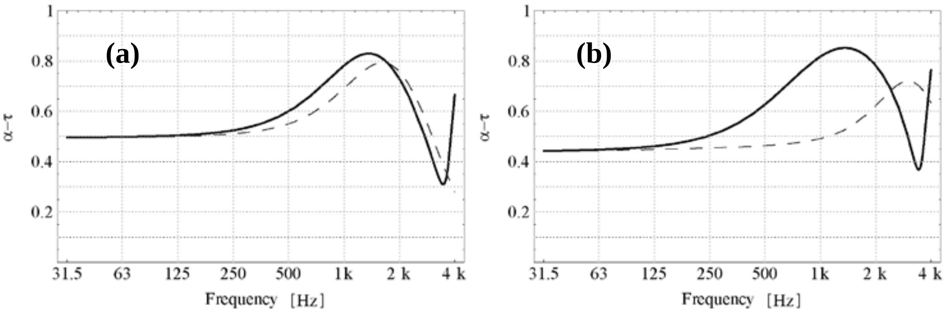

Fig. 3. The effect of a honeycomb in the cavity on the oblique incidence sound absorption characteristics of a DLMPP. The angle of incidence is (a) 30 degrees, and (b) 60 degrees. d = t =0.15mm, p=1%, D=50mm. Solid line: With honeycomb; Dashed line: Without honeycomb.

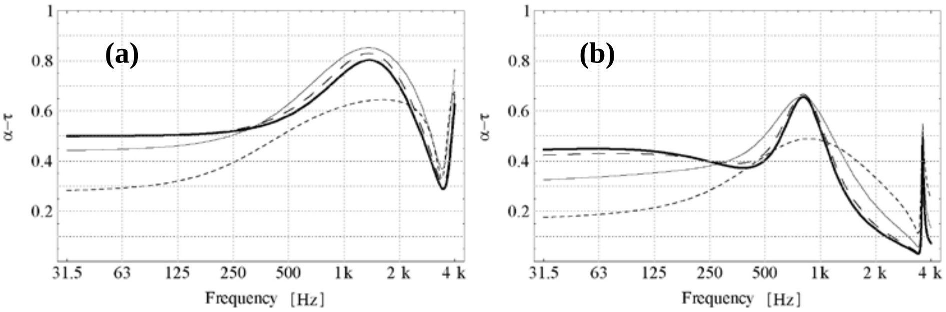

Fig. 4. The effect of the angle of incidence on the oblique incidence sound absorption characteristics of a honeycomb attached DLMPP. (a) d = t =0.15mm, p=1%, D=50mm， (b) d = t =0.5mm, p=0.64%, D=50mm. The angles of incidence are as follows: Solid line: Normal incidence; Dashed line: 30 degrees; Thin line: 60 degrees; Dotted line: 78 degrees.

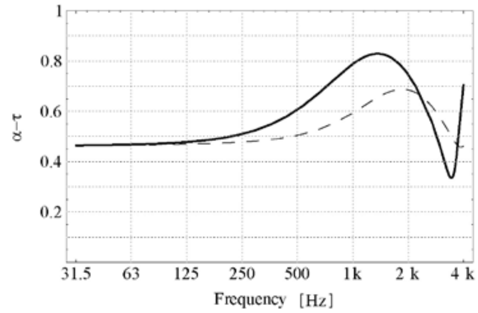

Fig. 5. The effect of the honeycomb in the cavity on the field-incidence-averaged sound absorption characteristics of a DLMPP. $d = t$ =0.15mm, p=1%, D=50mm. Solid line: With honeycomb; Dashed line: Without honeycomb.

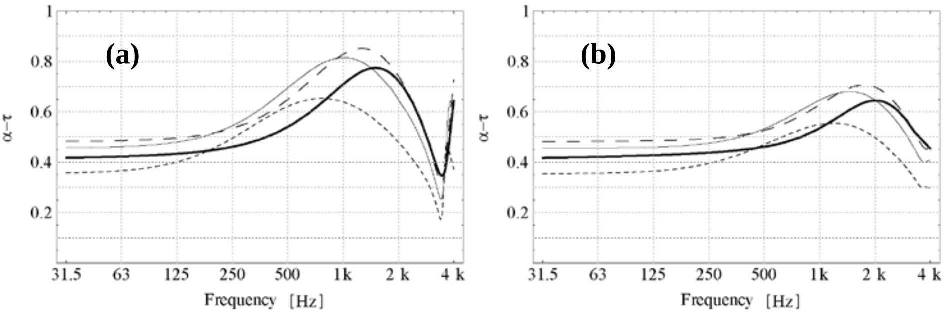

Fig. 6. The effect of the thicknesses of the MPPs of a DLMPP. d =0.15mm, p=1%, D =50mm. (a) With honeycomb, and (b) without honeycomb. Solid line: t = 0.1mm; Dashed line: t = 0.2mm; Thin line: t = 0.4mm; Dotted line: t = 0.8mm.

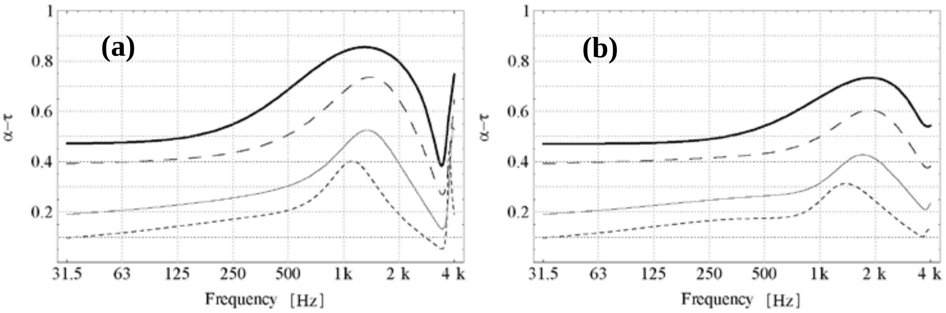

Fig. 7. The effect of the hole diameters of the MPPs of a DLMPP. *t* =0.15mm, *p*=1%, *D* =50mm. (a) With honeycomb, and (b) without honeycomb. Solid line: *d* = 0.1mm; Dashed line: *d* = 0.2mm; Thin line: *d* = 0.4mm; Dotted line: *d* = 0.8mm.

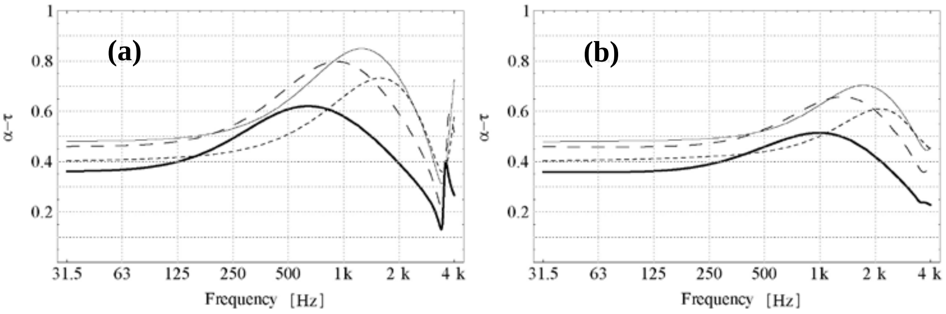

Fig. 8. The effect of the perforation ratios of the MPPs of a DLMPP. $d = t$ =0.15mm, D =50mm. (a) With honeycomb, and (b) without honeycomb. Solid line: p = 0.2%; Dashed line: p = 0.4%; Thin line: p = 0.8%; Dotted line: p = 1.6%.

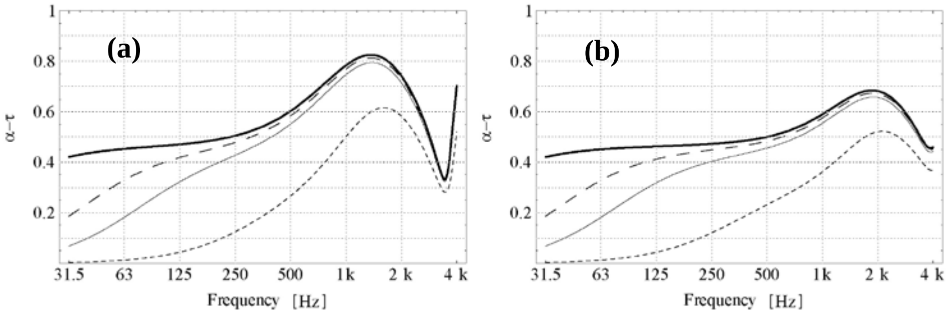

Fig. 9. The effect of the surface densities of the MPPs of a DLMPP. $d = t$ =0.15mm, p =0.1%, D =50mm. (a) With honeycomb, and (b) without honeycomb. Solid line: M = 3.0 kg/m²; Dashed line: M = 1.0 kg/m²; Thin line: M = 0.5 kg/m²; Dotted line: M = 0.1 kg/m².