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# **Sound absorption characteristics of a honeycomb-backed microperforated panel absorber: revised theory and experimental validation \***

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## **ABSTRACT**

**A microperforated panel (MPP) absorber is known as one of the most promising alternatives of the next-generation sound absorbers. However, MPPs are usually made of thin limp materials and need to be reinforced by a supporting element. The authors proposed to use a honeycomb attached behind an MPP for this purpose, and have shown that the honeycomb in the back cavity of an MPP absorber is not only useful to stiffen the MPP but improves its sound absorption performance, particularly at low frequencies. In the authors' previous studies an electro-acoustical circuit model was used to analyse its sound absorption characteristics, however, the model inevitably includes an approximation, and more exact theory needs to be established for better prediction of its characteristics. In this paper, the absorber is analysed with the wave theory based on Helmholtz-Kirchhoff integral equations. First, the formalism based on the Helmholtz-Kirchhoff integral is presented. Next, an experiment is made to validate the theory. Finally, a parametric study is made to discuss the effect of the parameters of the sound absorbing system on its sound absorption characteristics.**

INCE subject classification numbers: 35.6, 35.7, 35.1

\*This paper is a revised and extended version of one presented at INTER-NOISE 2009 [1]

## 1. INTRODUCTION

A micriperforated panel (MPP) is a thin panel with submillimetre perforations made out of arbitrary material, e.g., metal, plastics, etc<sup>2-5</sup>. An MPP is considered to be most promising among next-generation sound absorbing materials. It has durability and designability, which are not expected with conventional porous materials. Usually, an MPP is placed in front of a rigid-back wall with an air-cavity in-between, and Helmholtz resonators are produced with its perforation and the air-back cavity. This offers high sound absorption performance in relatively wide frequency range from mid to high frequencies. Since Maa's pioneering works, many studies have been conducted on the application of MPPs for various purposes including attenuating noise in small rooms<sup>6,7</sup>, duct silencing systems<sup>8</sup>, acoustic window systems<sup>9</sup>, noise barriers<sup>10</sup>, etc.

However, as MPPs are thin and in many cases limp, they are not strong enough for room interior surfaces in buildings. Therefore, MPPs need to be reinforced by some means to make them stiff enough for room interior surfaces. There are some means to stiffen thin MPPs, e.g., elastic support, etc<sup>11-12</sup>, but the authors' previous studies prove that the use of a honeycomb can be effective in both structurally and acoustically<sup>12-13</sup>. In the same studies the acoustical effect of honeycombs behind an MPP was studied both theoretically and experimentally, and it was found that a honeycomb can improve the sound absorption performance of a simple single-leaf MPP absorber, particularly at low frequencies. The authors also made a basic study on a honeycomb backed double-leaf MPP absorber (which is composed of two MPP leaves with a rigid-back wall, and two cavities are filled with honeycombs)<sup>14</sup>. In these studies theoretical analyses are made using simple electro-acoustical equivalent circuit models. However, in the case of a simple single-leaf MPP absorber the electro-acoustical equivalent circuit analysis must inevitably deal with the MPP impedance approximately for the sound wave incident on the back side of the MPP

from the cavity. Therefore, for more precise analyses and detailed discussions, a more sophisticated analysis needs to be employed. In this study, a single-leaf MPP absorber with a honeycomb in the cavity is analysed with Helmholtz-Kirchhoff integral formulation and analytical strict solution is derived in closed form. The formulation is similar to that used in the work by Toyoda et al<sup>15</sup>, though their work is focussed on the sound insulation of a panel. The solution is validated with experimental results, and also compared with the results by the electro-acoustical equivalent circuit model<sup>12-13</sup> to clarify the difference between the two theories.

## 2. ANALYSIS

### 2.1 Model

Figure 1 shows the model of a honeycomb-backed single MPP absorber for the analysis. A single-leaf MPP of infinite extent is lying in the  $x$ - $y$  plane, on which a plane wave of unit pressure amplitude is incident with an angle  $\theta$ . The parameters of the MPP are: thickness  $t$ , hole diameter  $d$ , perforation ratio  $p$ , surface density  $M$ , and specific acoustic impedance  $Z$ . The depth of the air cavity, which is filled with the honeycomb, is  $D$ , therefore honeycomb thickness is also  $D$ . The displacement of the sound induced vibration of the MPP is defined as  $w(x)$ . Time factor  $\exp(-i\omega t)$  is suppressed throughout. The specific acoustic impedance of the MPP  $Z=r-i\omega m$  is descibed as the following Maa's formulae<sup>3</sup>. Note that all impedances are normalised to the air impedance  $\rho_0 c_0$ .

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

$$\omega m = \frac{\omega t}{p c_0} \left( 1 + \frac{1}{\sqrt{9 + \frac{k^2}{2}}} + 0.85 \frac{d}{t} \right) \quad (2)$$

with

$$k = d \sqrt{\frac{\omega \rho_0}{4\eta}} \quad (3)$$

where  $\rho_0$  is the air density,  $c_0$  the sound speed in air,  $\omega$  the angular frequency,  $\eta$  the air viscosity ( $=1.789 \times 10^{-5}$  [Pa s]).

## 2.2 Basic formulae and solution

The surface pressure of the MPP's illuminated side  $p_1(x,0)$  is, by using a Helmholtz-Kirchhoff integral, described as:

$$p_1(x,0) = 2p_i(x,0) - 2 \int_{-\infty}^{\infty} \left[ p_1(x_0) \frac{\partial G(r|r_0)}{\partial n} - G(r|r_0) \frac{\partial p_1(x_0)}{\partial n} \right]_{z=0} dx_0, \quad (4)$$

where  $p_i$  is the pressure of the incident wave,  $n$  is the outward normal, and  $G(r|r_0) = (i/4)H_0^{(1)}(k_0|r-r_0|)$ .  $H_0^{(1)}$  is the the first kind Hankel function of order zero. The boundary condition on the surface of illuminated side is:

$$\frac{\partial p_1(x_0)}{\partial n} = \rho_0 \omega^2 w(x) + ik_0 A_m \Delta p(x_0), \quad (5)$$

where  $\Delta p$  is the pressure difference between both side surfaces of the MPP,  $A_m = \rho_0 c_0 / Z$ ,  $k_0$  is the wavenumber in the air, and  $Z$  is the specific acoustic impedance of the MPP. From the above equations, the surface pressure of the MPP's illuminated side  $p_1(x, 0)$  is<sup>16</sup>:

$$p_1(x, 0) = 2p_i(x, 0) + \frac{i}{2} \int_{-\infty}^{\infty} [\rho_0 \omega^2 w(x_0) + iA_m k_0 \Delta p(x_0)] H_0^{(1)}(k_0 |x - x_0|) dx_0. \quad (6)$$

In the air cavity the pressure and the particle velocity are generally expressed in the following forms:

$$p_2(x, z) = (Xe^{ik_0 z \cos \theta} + Ye^{-ik_0 z \cos \theta})e^{ik_0 x \sin \theta}, \quad (7)$$

$$v_2(x, z) = \frac{\cos \theta}{\rho_0 c_0} (Xe^{ik_0 z \cos \theta} - Ye^{-ik_0 z \cos \theta})e^{ik_0 x \sin \theta}, \quad (8)$$

where,  $X$  and  $Y$  are the pressure amplitude of the wave in the cavity propagating in  $+z$  and  $-z$  directions, respectively. In the present case, a honeycomb is inserted in the cavity. By the effect of the honeycomb the sound wave is assumed to propagate only in the direction normal to the back wall, i.e.,  $\pm z$  direction ( $\theta=0$ ), therefore, in eqns.(7) and (8),  $\theta=0$  is applied to  $\cos \theta$  in the brackets. The boundary conditions in the air cavity are as follows:

$$v_2(x, 0) = -i\omega w(x) + \frac{\Delta P(x)}{Z} \quad (9)$$

$$v_2(x, D) = 0 \quad (10)$$

From the eqns. (7)-(10), the complex pressure amplitudes,  $X$  and  $Y$ , are obtained, and from  $X$  and  $Y$  the surface pressure on the back side (transmitted side) is derived. The displacement of the sound induced vibration of the MPP,  $w(x)$ , is expressed in the following form by using the panel's unit response for vibration  $u(x)$ :

$$w(x) = \int_{-\infty}^{\infty} [p_1(\xi, 0) - p_2(\xi, 0)] u(x - \xi) d\xi \quad (11)$$

The above all equations are solved by Fourier transform technique. The Fourier transform of the unit response  $u(x)$ ,  $U(k)$ , is expressed as follows, when the panel's flexural rigidity is neglected for the simplicity.

$$U(k) = \frac{1}{2\pi(-M \omega^2)} \quad (12)$$

The reflected pressure is now derived as:

$$P_r(x, z) = \left[ 1 + \frac{i\rho_0 \omega^2 \Gamma_1(k_0 \sin\theta) - k_0 A_m \{A_1 \Gamma_1(k_0 \sin\theta) + A_2\}}{k_0 \cos\theta} \right] \exp[i(k_0 \sin\theta x - k_0 \cos\theta z)] \quad (13)$$

where  $\Gamma_1$ ,  $A_1$ ,  $A_2$  are substantially complicated functions including the MPP impedance, the cavity depth, etc, and expressed as follows:

$$\begin{aligned}
\Gamma_1 &= \frac{2}{H_1 J}, \\
A_1 &= \frac{H_2}{H_1}, \quad A_2 = \frac{2}{H_1}, \\
B_1 &= \frac{\rho_0 c_0}{\cos \theta}, \quad B_2 = \frac{B_1}{1 - \exp[2i\varphi]}, \\
C &= i\omega, \quad F = 1 + \exp[2i\varphi], \quad G = B_2 F, \\
H_1 &= 1 + N + \frac{G}{Z_1}, \quad H_2 = Z_1 + CG, \\
J &= \frac{1}{2\pi U_1} - \frac{H_2}{H_1}, \quad N = \frac{k_0 A_m}{k_0 \cos \theta}, \\
Z_1 &= \frac{i\rho_0 \omega^2}{k_0 \cos \theta}, \quad \varphi = k_0 D \cos \theta
\end{aligned} \tag{14}$$

The oblique incidence absorption coefficient is derived as  $\alpha_\theta = 1 - |P_r|^2$ . Field-incidence averaged absorption coefficient, which corresponds to diffuse field incidence, is taken by averaging  $\alpha_\theta$  over 0 to 78 degrees of the angle of incidence in the half sphere.

### 3. EXPERIMENTAL VALIDATION

An experimental study was conducted to validate the present theory. The specimens used in the experiment are listed in Table 1. The experiment was done in a reverberation room with the volume of 513 m<sup>3</sup> and the surface area of 382 m<sup>2</sup>. The area of the specimens is 10 m<sup>2</sup>. The specimens are set on the rigid floor: the MPPs were put (not bonded to the honeycomb) on the honeycombs (made of aluminium) set on the floor. The reverberation absorption coefficients were measured in accordance with JIS A1419 (compatible with ISO 354). The results of



comparison with the present theory for the Specimens C, D, E and F are shown in Fig. 2 (a)-(d). In these figures also the results by the electro-acoustical equivalent circuit model<sup>12-13</sup> are shown for comparison. In the equivalent circuit model calculation, the total impedance of the honeycomb-backed MPP absorber is approximately given as:

$$Z = r - i\omega m + z_h \quad (15)$$

where  $z_h$  is the impedance of the honeycomb modelled as a group of tubes<sup>13</sup>.

The results by the present theory are in good agreement with the experimental results. The present theory shows better agreement with experimental results than the electro-acoustical equivalent circuit model: In the equivalent circuit model results, the peak of the main MPP resonance absorption at mid-frequencies appears at higher frequencies than the experimental and the present wave theory results. The peak values in the equivalent circuit model results is lower than those of the present wave theory that are closer to the experimental results.

Similar results are obtained for the Specimens A and B: they are not presented here, because in these specimens the agreement is as good as the others and no special feature is observed. Thus, the present theory is more appropriate and can offer better prediction than the electro-acoustical equivalent circuit model analysis.

#### 4. NUMERICAL EXAMPLES – COMPARISON WITH EQUIVALENT CIRCUIT MODEL

The effect of honeycomb does not appear in the case of normal incidence<sup>12-13</sup>, therefore the discussions are made only in the case of oblique and diffuse field incidence. (Diffuse field

incidence characteristics are calculated as a field-incidence averaged value in the calculation.) In the following calculations the sound induced vibration of the MPP leaf itself is not taken into account.

Figure 3 compares the results by the present theory and the electro-acoustical equivalent circuit model for a honeycomb-backed single MPP absorber and a single MPP absorber without honeycomb in the case of oblique incidence ( $\theta=60$  degrees). By the effect of the honeycomb the peak frequency shifts to lower frequencies, and in the case without honeycomb, the two theories are in agreement with each other. But, in the case of honeycomb-backed MPP, the present theory and electro-acoustical equivalent circuit model show different behaviour: the present wave theory gives a broader absorption peak. Therefore, this discrepancy is caused by the difference in treatment of the MPP impedance between the two theories: In the equivalent circuit model the cosine factor is applied to the MPP impedance as local reacting, although the incidence from the backside of MPP becomes almost normal due to the effect of the honeycomb. In the present wave theory this point is taken into account – the MPP impedance is given as a boundary condition to the surfaces and treated without cosine factor.

Next, the results for a honeycomb-backed MPP absorber in the case of field incidence are shown in Fig. 4 (a). For reference, Fig. 4 (b) shows the results in the case without a honeycomb. From these figures, it is found that the peak shifts to lower frequencies and becomes more significant also in the diffuse field incidence condition. This tendency appears more significantly in the result calculated by the present theory, which shows broader absorption characteristics. On the other hand, in the case without honeycomb the present wave theory and the electro-acoustical equivalent circuit give completely the same results. From these results, it is realised that there is the following difference in the treatment of honeycomb between the present wave theory and equivalent circuit model: the wave reflected by the back wall that is incident upon the back side

of the MPP is primarily incident normally by the effect of the honeycomb. However, in the equivalent circuit model the cosine factor is applied to the MPP impedance, which eventually results in dealing with the sound incidence from backside as if it were obliquely incident. In the present theory the wave incident from back side is treated as normal incident. This difference causes the discrepancy between the results by the two theories. Therefore, even in the case of a single-leaf MPP absorber, when a honeycomb is used, it is more appropriate to use the present wave theory.

## **5. CONCLUDING REMARKS**

In this paper, the sound absorption characteristics of a honeycomb-backed MPP absorber has been theoretically analysed by using a Helmholtz-Kirchhoff integral formulation. The analytical solution is obtained in a closed form. The theory was validated with experimental results: the theoretical results by the present theory showed good agreement with the experimental results.

The present theory was also discussed through comparisons with conventional electro-acoustical equivalent circuit model analysis. The present theory showed better agreement with the experimental results than the equivalent circuit model, therefore the present theory can offer better prediction for the sound absorption characteristics of a honeycomb-backed MPP absorber.

Detailed discussions were also made through numerical examples focussing on the difference between the present wave theory and the equivalent circuit model. The main cause of their difference is originated from the treatment of the MPP impedance in equivalent circuit model analysis. This problem is overcome in the present wave theory and proves that the present

wave theory is more appropriate for predicting the characteristics of a honeycomb-backed MPP absorber.

The acoustical effect of the honeycomb behind the MPP observed in this study is summarised as: (1) it enhances the absorption peak, and (2) it shifts the peak to the lower frequencies and broadens the peak, which are the same as the previous results.

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Table1. Specimens of honeycomb-backed single-leaf MPP for experiment

Specimen	MPP's parameters			*Honeycomb thickness (mm)
	$d$ (mm)	$t$ (mm)	$p$ (%)	
A	0.5	0.5	0.785	25
B	0.5	1.0	1.23	25
C	0.5	0.5	0.785	50
D	0.5	1.0	1.23	50
E	0.5	0.5	0.785	75
F	0.5	1.0	1.23	75

\*The back-cavity is filled with honeycomb in all specimens, therefore, the honeycomb thickness is identical to the depth of the cavity.

## Captions of figures

Fig. 1. Model of the single-leaf honeycomb-backed MPP absorber for analysis.

Fig.2. Comparison of the theoretical and experimental results. (a) Specimen C, (b) Specimen D, (c) Specimen E, and (d) Specimen F. Solid line: the present theory; Dotted line: electro-acoustical equivalent circuit; Dots: Measured results.

Fig.3. Calculated examples of oblique incidence absorption coefficient ( $\theta=60$  degrees).  $d = t = 0.15\text{mm}$ ,  $p=1.0\%$ ,  $D=50\text{mm}$ . Honeycomb backed cases: Thick solid line: the present theory, Dashed line: equivalent circuit model. Cases without honeycomb: Thin solid line: the present theory, Dotted line: equivalent circuit model - These two curves for the cases without honeycomb (thin solid and dotted lines) are overlapped completely.

Fig.4. The absorption characteristics of a single-leaf MPP absorber calculated by the present wave theory and the equivalent circuit model in the case of field incidence.  $d = t = 0.15\text{mm}$ ,  $p=1\%$ ,  $D=50\text{mm}$ . (a) honeycomb backed cases - solid line: the present theory, dashed line: equivalent circuit theory, (b) cases without honeycomb - solid line: the present theory, dotted line: equivalent circuit model. In (b) the two curves are overlapped each other.



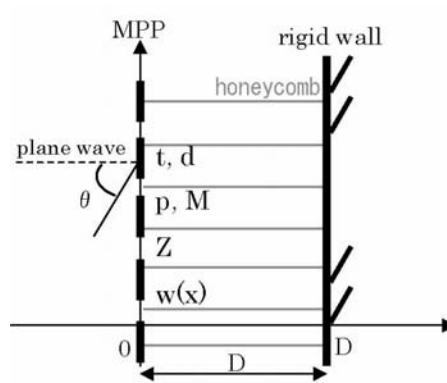


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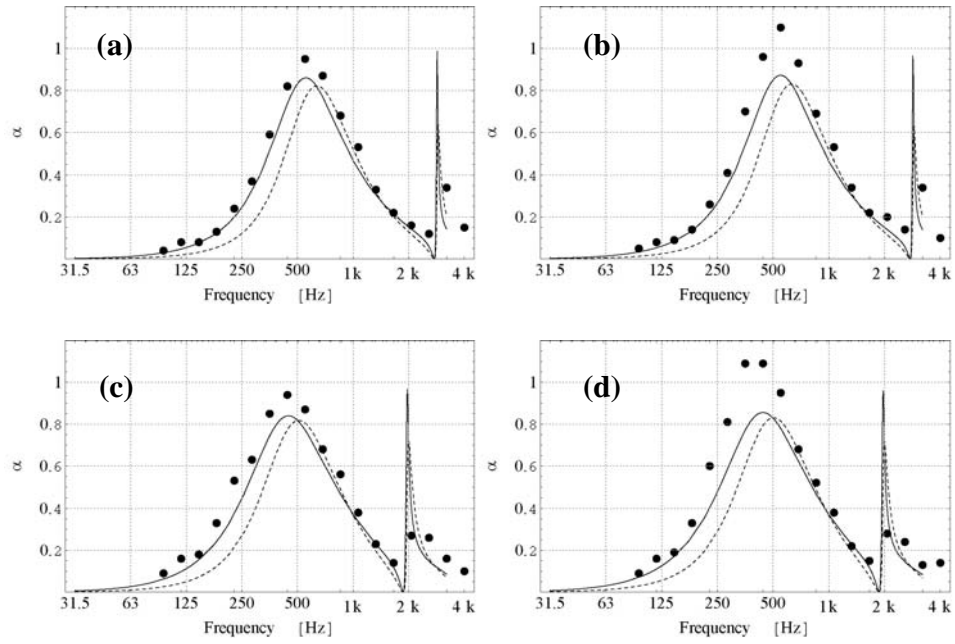


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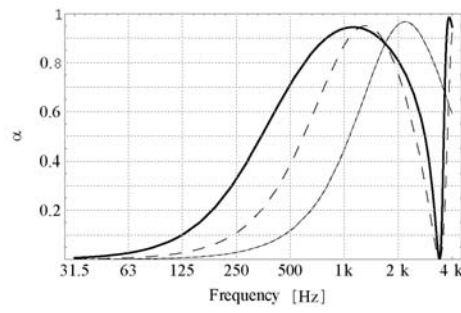


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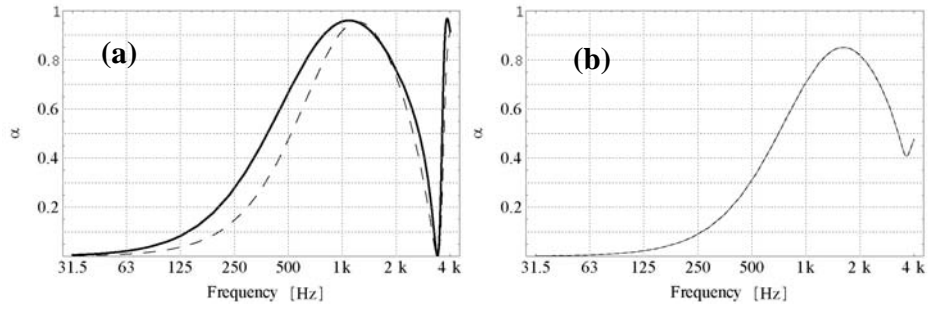


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