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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 wide-band 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 recognised. 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

Fig. 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

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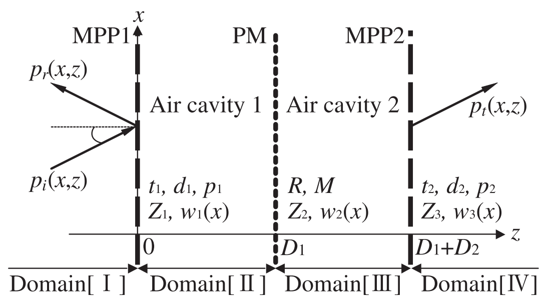

Fig. 1. Model for analysis of a triple-leaf sound absorbing structure with double-leaf MPP space absorber with a permeable membrane in the air cavity (M-P-M absorber).

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, $Z_{\rm MPP}$, is derived with the acoustic resistance r and acoustic reactance ωm as follows:

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

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, $Z_{\rm PM}$, is expressed as:

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

where ω is the angular frequency, η is the viscosity coefficient (1.789×10^{-5} Pa s). Here, $Z_{\rm PM}$ 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, $A_{m1} = \rho_0 c_0/Z_1$, 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 $Z_{\rm MPP}$ Eq. (1). From these equations, the pressure on the illuminated side surface of MPP1 is expressed as follows:

$$p_{d1}(x,0) = 2p_i(x,0) + \frac{i}{2}\int_{-\infty}^{\infty}[\rho_0\omega^2 w_1(x_0) + iA_{m1}k_0\Delta P_1(x_0)]H_0^{(1)}(k_0|x-x_0|)dx_0 \tag{8}$$

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:

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

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

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 $\pm z$ directions ($\theta = 0$), $\theta = 0$ is substituted into $\cos\theta$ in the right hand side, i.e., $\cos\theta = 1$.

The boundary conditions are as follows:

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

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

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

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

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 $Z_{\rm MPP}$ in Eq. (1), Z_2 is substituted with $Z_{\rm PM}$ 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:

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

The boundary condition on the surface is:

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

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: