A Basic Study on Double-leaf Microperforated Panel Absorbers
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Abstract
Microperforated panel (MPP) absorbers are one of the most promising alternatives for next-generation sound absorbing materials. They are typically used as ceilings or other interior surfaces of a room backed by an air-cavity with a rigid back wall. MPP absorbers can show their efficiency only when they have a back cavity, because they cause sound absorption due to the resonance by a Helmholtz-type resonator formed together with a back cavity. In order to create an efficient sound-absorbing structure with MPPs alone, a double-leaf MPP is studied, which is composed of two MPPs set in parallel with an air-cavity in-between without a rigid back wall. In this study, the posterior leaf (the MPP on the back side) plays the role of the back wall in the conventional setting to cause the resonance-type absorption. Additionally, a double-leaf MPP can have high absorptivity on both sides to work efficiently for sound incidence from both sides, and can be used efficiently as space absorbers, eg, suspended absorbers or sound absorbing panels, etc. The sound absorption characteristics of the double-leaf MPP are theoretically analysed for normal incidence of a plane wave. The effects of various control parameters are discussed through a parametric study with numerical examples. The absorption mechanism and design principle are also discussed. The results show (1) that the resonance absorption similar to the conventional type MPP absorbers appears at middle-high frequencies, and (2) that considerable “additional” absorption can be obtained at low frequencies. This low-frequency absorption is similar to that of a double-leaf permeable membrane, and can be of advantage over the conventional type.

1. Introduction
A microperforated panel (MPP) absorber, which is composed of a panel with submillimeter holes backed by an air-cavity, is recently recognised as one of the most promising alternatives for next-generation sound absorbing materials because of its fibre-free nature and attractive features. It was first proposed by Maa [1-3]. Its applications, improvement and theoretical development have been studied extensively [4-11]. It is typically used for ceilings or room interior surfaces, backed by an air-cavity. MPP absorbers can work most efficiently only when they have a back cavity with a back wall, because their sound absorption is caused by a Helmholtz-type resonator formed together with a back cavity. In order to avoid this limitation and to create an efficient sound-absorbing system with MPPs alone, a double-leaf MPP, composed of two MPPs set in parallel with an air-cavity in-between without a rigid back wall, is proposed and studied theoretically in this paper.

In this sound absorbing structure, the posterior leaf (the MPP on the back side) plays the important role of the back wall in the conventional setting to form an air-cavity in-between, which is crucial to cause the Helmholtz-type resonance absorption. A double-leaf MPP (DLMPP) can thus be considered to cause an efficient absorption similar to the conventional type with a back wall, even though it does not have a back wall. By virtue of the absence of a rigid back wall, a DLMPP can be used for a space absorber or a sound-absorptive screen/partition, and this feature can be of great use in various situations in which a rigid backing is not available for setting MPPs against, and also it can enable MPPs for application to different parts of interior in buildings.

In this paper, an electro-acoustical equivalent circuit analysis is used to analyse the acoustic properties of a DLMPP. As it causes not only sound absorption but sound transmission through it as well, both sound absorption and transmission coefficients are considered, and the sound absorption performance is evaluated by the difference of these two coefficients, which signifies the ratio of energy absorbed in the structure. A parametric study through numerical examples is made to discuss the effect of the control parameters such as hole diameter, plate thickness (ie, tube length), perforation ratio, as well as the cavity depth. A proposal for the optimal design of a DLMPP is also attempted. Absorption mechanism is discussed through the calculated results of absorptivity and impedance.

2. THEORETICAL CONSIDERATION
Figure 1 shows the model for a DLMPP. MPP1 and MPP2 are placed in parallel with an air-cavity of depth D in-between. A plane sound wave of unit pressure amplitude is assumed to be normally incident upon
Both leaves have submillimeter perforation which is characterised by the following parameters: hole diameter ($d$), perforation ratio ($p$), and panel thickness (=tube length, $t$). This DLMPP can equivalently be described by the electrical circuit in Fig. 2.

According to the equivalent circuit, the total impedance of the DLMPP at the surface of MPP1, $Z_{tot}$, can be expressed by

$$Z_{tot} = R_1 - i\omega M_1 + \left(\frac{1}{Z(D)} + \frac{1}{R_2 - i\omega M_2 + \rho c}\right)^{-1} \tag{1}$$

where

$$R_{1,2} = \frac{32\eta}{p_{1,2}\rho c d_{1,2}^2} \left(1 + \frac{x_{1,2}^2}{32} + \frac{2x_{1,2}d_{1,2}}{8t_{1,2}} \right) \tag{2a}$$

$$M_{1,2} = \frac{t_{1,2}}{p_{1,2}\rho c} \left(1 + \frac{1}{x_{1,2}^2} + 0.85\frac{d_{1,2}}{t_{1,2}} \right) \tag{2b}$$

These equations are given by Maa’s pioneering work [1-3]. In Eqs (2), $\eta$ is the coefficient of viscosity, $\rho$ is air density, $\omega$ the angular frequency of the sound. Note that in these equations $d_{1,2}$ and $t_{1,2}$ are given in millimeter. The subscript 1 and 2 denote the association with the leaf 1 and 2.

Therefore, the sound absorption coefficient, $\alpha$, is given by the well-known formula:

$$\alpha = \frac{4\operatorname{Re}[Z_{tot}]}{(1 + \operatorname{Re}[Z_{tot}])^2 + \operatorname{Im}[Z_{tot}]^2} \tag{3}$$

The sound transmission coefficient, $\tau$, is given as the power consumed at the resistor $\rho c$ behind the MPP2, which is

$$\tau = \rho c \frac{2}{Z_{tot}} \frac{R_1 - i\omega M_1 + \rho c}{R_2 - i\omega M_2 + \rho c} \tag{4}$$

As the sound can transmit through the structure in this case, the sound absorption performance should be evaluated by the energy dissipated in the structure, which is expressed by the difference of the above two coefficients, $\alpha - \tau$. This will be used hereafter to discuss the sound absorption performance.

### 3. NUMERICAL EXAMPLES AND DISCUSSION

Figure 3 shows a typical example of the sound absorptivity of a DLMPP. The result is shown in the difference between sound absorption and transmission coefficients. A significant resonance peak at mid-frequencies, which is typical of MPP absorbers, is observed. The peak is as significant as that of a conventional MPP absorber with a rigid-back wall. More interestingly, the absorptivity takes relatively high values at low frequencies: the curve shows a plateau around 0.5 at low frequencies (below 500 Hz). This feature is not observed in a conventional MPP absorber with rigid-back wall. Maa [1-3] studied a double-leaf MPP with a rigid-back wall. More interestingly, the absorptivity takes relatively high values at low frequencies: the curve shows a plateau around 0.5 at low frequencies (below 500 Hz). This feature is not observed in a conventional MPP absorber with rigid-back wall. Therefore, this feature of the current DLMPP is a significant advantage over conventional wall-backed MPPs.

In order to interpret this feature, the surface
impedances of the DLMPPs in Fig 3 are shown in Fig 4.

The real part, the resistance, shows a drop around the resonance frequency, where the imaginary part, the reactance, becomes zero. The value of the resistance at the resonance frequency is around unity (in the unit of the specific impedance of air, \(\rho c\)); the absorptivity is maximised when the resistance, produced by the holes of MPPs, is around unity. However, the resistance takes higher value around 3 at low frequencies where the absorptivity shows a plateau. At low frequencies, the cavity impedance tends to infinity with the frequency decreased, and then the impedance of the structure is maximised when the resistance, produced by the holes maximises as a whole (or the DLMPP, Fig. 5). In order to demonstrate this similarity, the absorptivity of a DLMPP is compared with that of a double-leaf membrane (DLPM) having the same flow resistance of permeable structure. In these permeable structures the sound absorption is caused by their acoustic flow resistance \(2\rho c\) [12,13]: in these permeable structures the sound absorption is caused by their acoustic flow resistance only. The DLMPP also behaves as a permeable structure such as the permeable membrane structures, and demonstrates very similar characteristics. For this low frequency absorption, according the authors' previous studies, the optimal value of the flow resistance of permeable structure is theoretically derived as \(2\rho c\) [13]. In the case of DLMPP, the optimal value of the resistance is the same (the surface resistance is \(3\rho c\), because the impedance of the air behind the posterior MPP is here included in it.) In order to demonstrate this similarity, the absorptivity of a DLMPP is compared with that of a double-leaf permeable membrane (DLPM) having the same flow resistance as the resistance of the DLMPP (Fig. 5). In this example, the calculations were performed with considering the effect of the bulk vibration of the MPP leaves: the bulk mass reactance of MPP, \(-i\omega m_1\) and \(-i\omega m_2\) (where, \(m_1\) and \(m_2\) are the surface density of MPP1 and 2, respectively), are added in parallel to the impedance of MPP1 and 2, respectively. The DLPM results were calculated according to the authors' previous study [12] including the membrane vibration.

**Figure 3:** Typical results of the absorptivity of a DLMPP, shown in the difference of absorption and transmission coefficients with various hole diameters \((d_1=d_2)\) as a parameter: \(0.1\ldots0.8\) mm. Other parameters are: \(p_1=p_2=0.8\%\), \(t_1=t_2=0.2\) mm, \(D=50\) mm. The figure shows that \(d_1=d_2=0.2\) mm maximises the resonance absorption peak.

**Figure 4:** Surface impedance of DLMP presented in Figure 3. The values are shown in the unit of air impedance \(\rho c\). The optimal condition shown in Figure 3 is confirmed as the resistance approaches to unity.

**Figure 5:** Comparison of absorptivity of a DLMPP (top) and a double-leaf permeable membrane (bottom). The flow resistance of a leaf in the double-leaf membrane is adjusted to be the same as that of a MPP leaf in the DLMPP. The effect of the mass of the leaf is taken into account in these calculations. The parameter is the mass of the leaves (both leaves are supposed to be of the same mass) of the DLMPP or double-leaf membrane \(\text{[kg/m}^2\text{]}\).

mostly dominated by the series of the resistances of the MPPs. This condition is similar to that for a single- or a double-leaf permeable membrane at low frequencies [12,13]: in these permeable structures the sound absorption is caused by their acoustic flow resistance only. The DLMPP also behaves as a permeable structure such as the permeable membrane structures, and demonstrates very similar characteristics. For this low frequency absorption, according the authors' previous studies, the optimal value of the flow resistance of permeable structure is theoretically derived as \(2\rho c\) [13]. In the case of DLMPP, the optimal value of the resistance is the same (the surface resistance is \(3\rho c\), because the impedance of the air behind the posterior MPP is here included in it.) In order to demonstrate this similarity, the absorptivity of a DLMPP is compared with that of a double-leaf permeable membrane (DLPM) having the same flow resistance as the resistance of the DLMPP (Fig. 5). In this example, the calculations were performed with considering the effect of the bulk vibration of the MPP leaves: the bulk mass reactance of MPP, \(-i\omega m_1\) and \(-i\omega m_2\) (where, \(m_1\) and \(m_2\) are the surface density of MPP1 and 2, respectively), are added in parallel to the impedance of MPP1 and 2, respectively. The DLPM results were calculated according to the authors' previous study [12] including the membrane vibration.
Below the resonance peak, the DLMPP shows the same characteristics as those of the DLPM. This indicates that a DLMPP has the same absorption mechanism as of a DLPM at low frequencies. The absorption mechanism of a DLMPP is thus interpreted as the combination of resonator type at mid-high frequencies and porous type at low frequencies. Therefore, to obtain the best performance from DLMPP, the control parameters should be set so that the surface resistance should be \( \rho \) around the resonance frequency and \( 3 \rho \) below it.

It should also be noted that the effect of the plate mass appears at low frequencies in the same manner as in a DLPM: lighter leaves cause more significant drop in absorptivity at low frequencies. This is because the vibration of the leaf causes apparent decrease in acoustic flow resistance of the holes in DLMPP. The leaf mass of 2kg/m\(^2\) gives almost the same value as in the immobile case at frequencies above 63 Hz, however, the leaves lighter than that shows considerable decrease in absorptivity at low frequencies. Therefore, when a DLMPP is made of lighter material, this effect should be taken into account in design. Detailed discussion on this subject will be presented in a separate publication [14].

4. Concluding Remarks

In order to make an efficient sound absorbing structure by MPPs only, a double-leaf MPP (DLMPP), consisting of two MPPs placed in parallel with an air layer in-between, without a back wall, has been proposed. A theory to predict its acoustic properties has been formulated extending the basic theory established by Maa [2]. A DLMPP has no back wall, and sound transmission occurs. Its sound absorptivity is evaluated by the difference of absorption and transmission coefficients to describe the ratio of the energy dissipated in the DLMPP.

Numerical examples demonstrate the potential of a DLMPP: It shows a resonant peak absorption similar to the conventional MPP absorber, and more interestingly, substantial absorption at low frequencies where the conventional type is not efficient.

The absorption mechanism of a DLMPP has been discussed through comparison of results with those for a double-leaf permeable membrane (DLPM): The absorption mechanism of a DLMPP is a combination of resonance type similar to the conventional type at mid-high frequencies and an absorption by resistance at low frequencies similar to a DLPM. The effect of the mass of the leaf also appears in DLMPP, which suggests that lighter material can deteriorate the low-frequency absorptivity.

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6. References