A theoretical study on triple-leaf microperforated panel absorbers

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Title:

A theoretical study on triple-leaf microperforated panel absorbers (TLMPP)

３重微細穿孔板空間吸音体（TLMPP）に関する解析的研究

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1. Introduction

A microperforated panel (MPP) is a kind of perforated panels which has very small perforations of diameter less than 1 [mm] and perforation ratio less than 1 [%]. It is recently widely known as a substitution of porous materials, and is considered the most promising among "next-generation sound absorbing materials" [1-3]. MPPs are basically placed in front of a rigid-back wall with an air-back cavity in-between, which causes Helmholtz-type resonance sound absorption with its hole and the cavity.

On the other hand the authors proposed a double-leaf MPP space sound absorber (DLMPP) which is composed of two MPPs and an air cavity in-between [4]. A DLMPP is proposed to be used as a space sound absorber, and it shows Helmholtz-type resonance absorption at mid to high frequencies and an additional absorption at low frequencies which is produced by the acoustic resistance due to its acoustical permeability.

In this study, in order to propose more efficient MPP space sound absorber, adding an extra MPP leaf to a DLMPP, a triple-leaf MPP space sound absorber (TLMPP) is discussed. In the early studies on MPP absorbers electro-acoustical equivalent circuit analyses (EC) are widely used, however, in this study the wave theory (WT) is used. Also the results by EC and WT are compared for reference.

2. Theoretical model

The model for the theoretical analysis is shown in Fig. 1. The method of analyses for a TLMPP is similar to that for a DLMPP [4] and one can obtain the formulation by extending the theory in Ref. [4] by adding the equations relating to the third MPP leaf. Hereafter, only the outline of the theory is briefly introduced. As this study intends to clarify the fundamental feature of a TLMPP, the theoretical analysis is made in the case of the normal incidence of a plane wave. The surface pressures of the illuminated side and the back side of each MPP leaf are expressed by wave theory. Using them, the equations of continuation of the particle velocities of the both side surface of each MPP, and the equation of motion of each MPP leaf by sound induced vibrations are solved simultaneously.

The equation of continuation of the particle velocity of the illuminated side surface of MPP1 is expressed with the MPP1's acoustic impedance Z_1 as:

$$Z_1 = \frac{(P_i + P_r) - (P_{1+} + P_{1-})}{\left(\dfrac{P_i}{\rho c} - \dfrac{P_r}{\rho c}\right) + i\omega m_1} \quad . \tag{1}$$

The equation of continuation of the particle velocity of the back (transmitted) side surface of MPP1 is:

$$Z_1 = \frac{(P_i + P_r) - (P_{1+} + P_{1-})}{\left(\dfrac{P_{1+}}{\rho c} - \dfrac{P_{1-}}{\rho c}\right) + i\omega m_1} \quad . \tag{2}$$

The equation of motion of MPP1 due to the sound induced vibration is:

$$\left(P_i + P_r\right) - \left(P_{1+} + P_{1-}\right) = -\omega^2 m_1 w_1 \quad .$$ (3)

In the above equations, the following notations are used: in the air cavity between MPP1 and 2, the sound wave propagating into $+z$ direction is P_{1+} and that into $-z$ direction is P_{1-}, the vibration displacement of MPP1 is w_1, its surface density is m_1. The acoustic impedance of the MPP1, Z_1, is derived from Maa's theory [3]:

$$Z_1 = r_1 + i\omega m_1 \qquad ,$$ (4a)

$$r_1 = \frac{32\eta t_1}{p_1 d_1^2}\left(\sqrt{1 + \frac{k_1^2}{32}} + \frac{\sqrt{2}}{32}k_1\frac{d_1}{t_1}\right) \quad ,$$ (4b)

$$\omega m_1 = \omega t_1\left(1 + \frac{1}{\sqrt{9 + \frac{k_1^2}{2}}} + 0.85\frac{d_1}{t_1}\right) \qquad ,$$ (4c)

where $k_1 = d_1(\omega\rho/4\eta)^{1/2}$, ω is the angular frequency, d_1, t_1, p_1 are the hole diameter [m], thickness [m] and perforation ratio [%] of MPP1 respectively. η is the viscosity coefficient of air (17.9 μPa s).

Regarding MPP2 and 3, considering the same manner, the simultaneous equations for P_r, P_t, P_{1+}, P_{2+} are obtained. Solving all the equations, the reflected pressure P_r, and the transmitted pressure P_t are obtained. From them, the absorption coefficient α and the transmission coefficient τ are obtained. In the following, as a TLMPP is a space absorber and transmitted energy remains in the sound field, it is reasonable to evaluate the absorption efficiency by taking the energy actually dissipated in the structure, which is described by the difference of the absorption and transmitted coefficients, α - τ.

3. Results and discussion

3.1 General feature of a TLMPP

A TLMPP (A) is compared with (B) Common single MPP absorber with a back wall, (C) Common double-leaf MPP absorber with a back wall, and (D) DLMPP. The result of the comparison is shown in Fig. 2. In (A)-(D) all MPP parameters are kept as the same, and the cavity depths are kept constant.

The (A) shows α - τ of 0.4 - 0.5 at low frequencies. This low frequency absorption can be considered as that appears in the case of DLMPP [4] which is caused by the acoustic permeability of MPP leaves. At mid and high frequencies there are two peaks caused by Helmholtz-type resonance, and shows α - τ of around 0.7. In (B) and (C), as in the (A) a peak by Helmholtz-type resonator appears, but the sound absorption is limited to resonance and no other sound absorption appears: there is no additional low frequency absorption.

In (D), A DLMPP shows both peak and low frequency absorption, it shows only one resonance peak which

makes absorption frequency range narrower than (A) TLMPP. From the results above, a TLMPP shows wider sound absorption frequency range due to the wider resonance peak with additional low frequency absorption.

3.2 Parametric studies

In this section the effects of parameters of a TLMPP on its sound absorption characteristics are discussed through the theoretical results. The reference values of each parameter are determined as in Table 1. The parameters are changed around the reference values, however, the three MPP leaves are assumed to have the same parameters. The parameters discussed here are the perforation ratios (p_1, p_2, p_3), hole diameters (d_1, d_2, d_3), thicknesses (t_1, t_2, t_3), air cavity depths (D_1, D_2), and surface densities (M_1, M_2, M_3).

 (1) Effects of the perforation ratio, hole diameter and thickness

The effects of the perforation ratio, hole diameter and thickness are shown in Figs. 3, 4, and 5, respectively. In all cases the α - τ is changing accordingly at low frequencies, however, it can be observed that there is the optimal value for each parameter that makes α - τ the highest. Detailed discussion on this phenomenon is suppressed by the limitation of pages, the α - τ becomes the highest when each parameter becomes the value that makes the total normalised acoustic resistance of the absorbing structure become around 2.0 - 2.5. On the other hand at the resonance peak the α - τ is the largest when the total normalised acoustic resistance becomes around 1.0. Regarding the peak frequency, it shifts to higher frequencies when the perforation ratio becomes larger, or the hole diameter and thickness becomes smaller.

 (2)The effects of the other parameters

The effects of the other parameters, the cavity depths and surface densities, are remarked here: numerical examples are not shown because of limited spaces. The effect of the air cavity depth, D_1 affects the peak at higher frequency, and $D_1 + D_2$ affects the peak at lower frequency. The effect of the surface density of the MPP leaves, the effects of the sound induced vibration becomes more significant at lower frequencies, therefore smaller surface density gives lower absorption efficiency at low frequencies. However, if the surface density is heavier than 2.0kg/m^2 the results do not show the effect of the sound induced vibration.

3.3 The comparison of WT and EC

An example of the comparison of the results by WT and EC. The both results are qualitatively in agreement. However, in some frequency range they show a significant discrepancy. In general, EC gives larger value than WT at low frequencies, and the difference can be more than 1.0. On the other hand, from mid to high frequencies, EC shows narrower resonance peak than WT. Thus, EC can be used as a simple and easy-to-use prediction method, but WT should be used for more precise prediction.

References

[1] D-Y. Maa, Theory and design of microperforated panel sound-absorbing constructions, Scientia Sinica, 18, 55-71 (1975).

[2] D-Y. Maa, Microperforated-panel wideband absorbers, Noise Control Eng. J., 29, 77-84 (1987) .

[3] D-Y. Maa, Potential of microperforated panel absorber, J. Acoust. Soc. Am., 104, 2861-2866 (1988) .

[4] K. Sakagami, T. Nakamori, M. Morimoto and M. Yairi, Double-leaf microperforated panel space absorbers: A revised theory and detailed analysis, Appl. Acoust., 70, 703-709 (2009).

[3] D-Y. Maa, Potential of microperforated panel absorber, J. Acoust. Soc. Am., 104, 2861-2866 (1988) .

[4] K. Sakagami, T. Nakamori, M. Morimoto and M. Yairi, Double-leaf microperforated panel space absorbers: A revised theory and detailed analysis, Appl. Acoust., 70, 703-709 (2009).

Table 1: Reference values for the parametric studies

Parameters	
Diameter of perforations d_1, d_2, d_3 [mm]	0.3
Thickness t_1, t_2, t_3 [mm]	0.3
Separation of holes b_1, b_2, b_3 [mm]	0.3
Percentage perforation p_1, p_2, p_3 [%]	1.0
Air cavity depth D_1, D_2 [mm]	25
Suface density M_1, M_2, M_3 [kg/m^2]	1.0

Captions of figures

Fig. 1   Model of a TLMPP for theoretical analyses.

Fig. 2   A Comparison of the sound absorptivity of TLMPP (α - τ: red line), with DLMPP(α - τ: green line), the absorption coefficients of conventional single and double MPP absorbers (black and blue lines, respectively).

Fig. 3   The effect of the perforation ratio on α - τ of a TLMPP absorbers. $p_1 = p_2 = p_3 = 0.25$ (green), 0.5 (blue), 1.0 (red), 2.0 (solid black), 4.0 (dashed black) (%). The other parameter values are the same as in Table.1.

Fig. 4   The effect of the diameter of perforations on α - τ of a TLMPP absorbers. $d_1 = d_2 = d_3 = 0.1$ (green), 0.2 (blue), 0.3 (red), 0.6 (solid black), 1.2 (dashed black) (mm). The other parameter values are the same as in Table.1.

Fig. 5   The effect of the thickness on α - τ of a TLMPP absorbers. $t_1 = t_2 = t_3 = 0.1$ (green), 0.2 (blue), 0.3 (red), 0.6 (solid black), 1.2 (dashed black) (mm). The other parameter values are the same as in Table.1.

Fig. 6   A comparison of the absorptivity of a TLMPP absorber estimated by wave theory (red line), with that estimated by equivalent circuit (black line). $p_1 = p_2 = p_3 = 0.5$ (%). The other parameter values are the same as in Table 1.
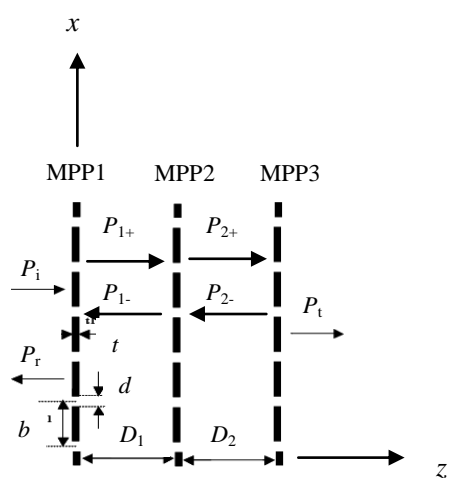
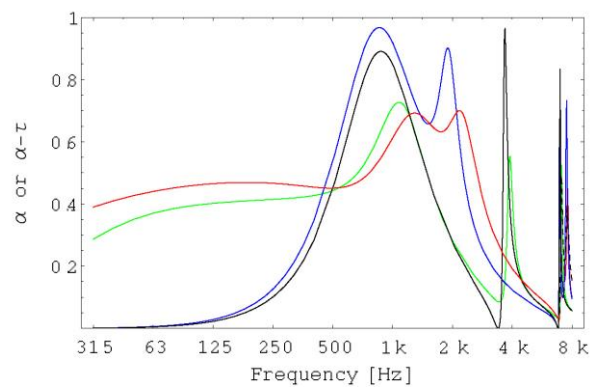Fig. 1　Model of a TLMPP for theoretical analyses

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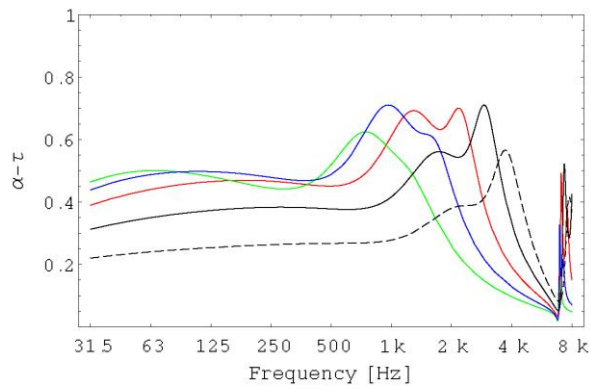(black and blue lines, respectively).

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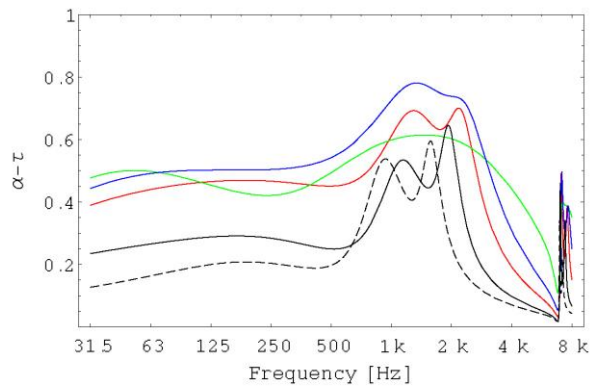
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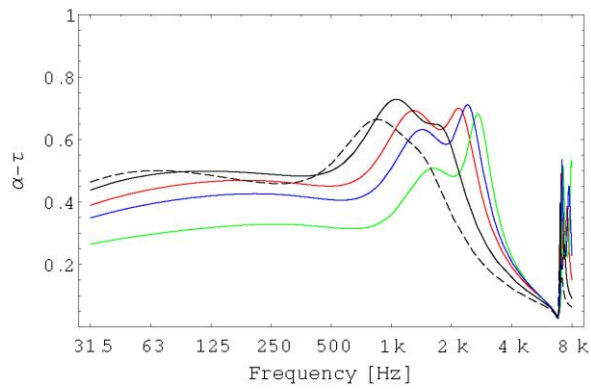
Fig. 5 The effect of the thickness on α - τ of a TLMPP absorbers. $t_1 = t_2 = t_3 = 0.1$ (green), 0.2 (blue), 0.3 (red), 0.6 (solid black), 1.2 (dashed black) (mm). The other parameter values are
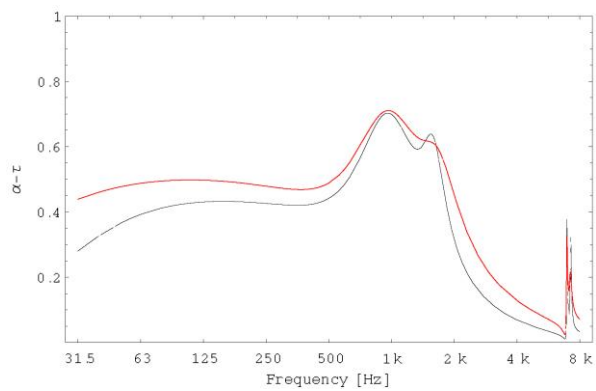
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