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ACOUSTICAL LETTER

Absorption characteristics of a double-leaf membrane with a permeable leaf and an absorptive layer in its cavity

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1. Introduction

In the previous papers,[1-3] the authors have established and experimentally validated the theories to analyse the acoustic properties of double-leaf membranes of various type that are widely used in membrane-structure buildings, and discussions in the light of the theoretical results have revealed their acoustic properties including physical mechanism behind them.

In this letter, the outline of a further study on double-leaf membranes with a permeable leaf, in which the theoretical model is generalised so that the effect of an absorptive layer in the cavity can be taken into consideration, is presented. The generalised theory is outlined and the acoustic properties of double-leaf membranes with a permeable leaf and an absorptive layer in its cavity are discussed in the light of numerical examples.

2. Theoretical considerations

A double-leaf membrane with three-layered cavity in between is modelled as in Fig. 1: the two leaves are of infinite extent, and the surface densities and the tensions of Leaves 1 and 2 are m_1 and m_2, and T_1 and T_2, respectively. Leaf 1, on which a plane incident wave impinges at an angle θ, is supposed to be permeable and to have flow resistance Rh, where R is specific flow resistivity and h is the thickness. Leaf 2 is impermeable and has surface acoustic admittances A_3 (face) and A_4 (back). The cavity between the two leaves is modelled as being composed of three layers, each of which is of an arbitrary medium. With this assumption the model allows us to analyse almost all types of the cavity practically encountered.

For this structure the equations of motion of Leaves 1 and 2 and Helmholtz integral equations for all regions in the sound fields are formulated. This results in simultaneous integral-differential equations that can be solved analytically with the Fourier transform technique. Solving the system as above gives the reflected pressure $p_r(x,z)$ and the transmitted pressure $p_t(x,z)$ as:

$$p_r(x,z)=\frac{k_0\cos\theta(Rh-H_1)-\rho_0\omega+i\rho_0\omega^2[Rh\Gamma_1(k_0\sin\theta)+H_2\Gamma_2(k_0\sin\theta)]}{\Theta(k_0\sin\theta)}\exp[ik_0(x\sin\theta-z\cos\theta)], \quad (1)$$

$$p_t(x,z)=-\frac{i\rho_0c_0\omega\Gamma_2(k_0\sin\theta)}{\cos\theta+A_4}\cdot\exp[ik_0\{x\sin\theta+(z-z_3)\cos\theta\}], \quad (2)$$

where Γ_1, Γ_2, H_1, H_2 and Θ are all substantially complicated functions including the system parameters such as membrane's physical properties and absorptive layer's parameters. For more details of the analysis, readers should refer to Ref. 4).

Since the unit pressure amplitude is assumed for the incident wave, absorption and transmission coefficients are obtained as $\alpha=1-|p_r|^2$ and $\tau=|p_t|^2$, respectively. Acoustical properties in diffuse sound field, which is of greater practical interest, can be evaluated with field-incidence-averaged coefficients, which are the coefficients averaged over the range of 0 to 78 degrees in angle of incidence. In the following field-incidence-averaged values are only used. One should note that absorption coefficients include transmitted energy that is described by transmission coefficients, and they do not represent the real energy loss actually taking place in the system. Therefore, the difference between absorption and transmission coefficients, $\alpha-\tau$, is used in this paper to discuss the absorption characteristics.

3. Numerical examples and discussion

In the following calculations the specific acoustic impedance and the propagation constant of absorptive layers in the cavity are given according to Miki's empirical formulae.[5] For the propagation constant, anisotropic nature of porous materials is considered.[6] The following values of the parameters are used unless otherwise noted: $m_1=m_2=1.0$ [kg/m^2], $T_1=T_2=1.0$ [N/m], $A_3=A_4=0.026$, $Rh=1.0\times10^3$ [Pa·s/m] ($R=$

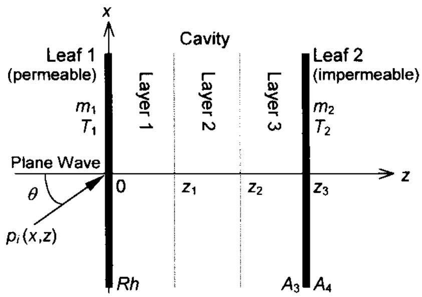

Fig. 1 Geometry of a modelled double-leaf membrane with an absorbent layer in its cavity.

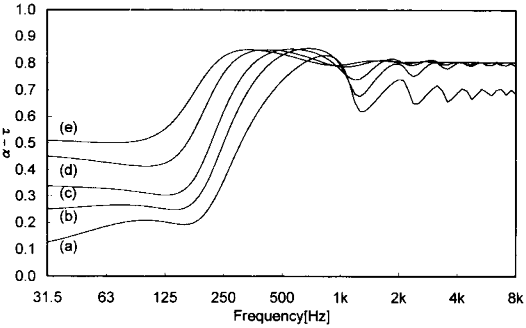

Fig. 2 Effect of the thickness of an absorptive layer in the cavity: (a) 0, (b) 0.025, (c) 0.05, (d) 0.10 and (e) 0.15 m, placed adjacent to Leaf 1. The cavity depth is 0.15 m in total. The flow resistivity R_f of the layer is 5.0×10^3 Pa•s/m^2.

2.0×10^6 [Pa•s/m^2], $h=5.0\times10^{-4}$ [m]), $\rho_0=1.2$ [kg/m^3], $c_0=340$ [m/s].

3.1 Effects of the thickness of the absorptive layer in the cavity

Figure 2 shows calculated results of $\alpha-\tau$ for a double-leaf membrane with different thickness of the absorbent layer in the cavity in comparison with that for the same double-leaf but without the absorbent layer. The absorbent is placed just behind Leaf 1, and the cavity depth is 0.15 m in total. The effect of the absorbent appears at almost all frequencies to increase $\alpha-\tau$; the effect is the most significant at low frequencies. This tendency is similar to that seen in the case of a double-leaf with two impermeable leaves.[3] At high frequencies, the effect of an absorptive layer is to increase $\alpha-\tau$. However, the increment does not change even if its thickness changes. This can be explained as follows: the absorptive layer in the cavity damps the resonances of the cavity, which makes dips in absorptivity less significant resulting in higher values when the characteristics are averaged over the different angles of incidence that cause the dips at different frequencies.

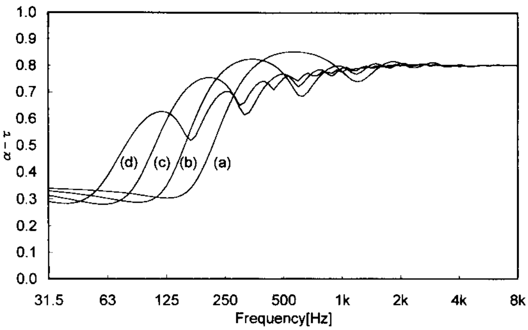

Fig. 3 Effect of the thickness of the air layer behind the absorbent in the cavity: (a) 0.10, (b) 0.25, (c) 0.55 and (d) 1.15 m. The thickness and flow resistivity of the absorbent in the cavity (placed adjacent to Leaf 1) are 0.05 m and 5.0×10^3 Pa•s/m^2.

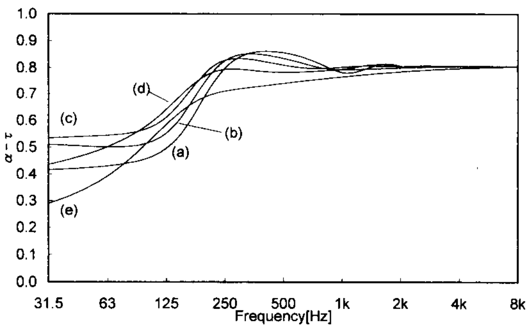

Fig. 4 Effect of the flow resistance (R_a) of the absorptive layer in the cavity. The cavity 0.15 m deep is filled with the absorbent. R_a=(a) 3.75×10^2, (b) 7.50×10^2, (c) 1.50×10^3, (d) 3.00×10^3 and (e) 6.00×10^3 Pa•s/m.

3.2 Effect of the thickness of the air layer behind the absorbent

Figure 3 shows the results of $\alpha-\tau$ in the case where an absorptive layer is placed just adjacent to Leaf 1 and the air layer behind the absorbent is changed. As the air layer becomes thicker, peaks and dips tend to appear at lower frequencies, and the peak at the lowest frequency becomes less significant. The same tendency is also seen in the case of an air layer only.[2] This is explained considering the general behaviour of a single-leaf permeable membrane: the $\alpha-\tau$ of a single-leaf permeable membrane lowers at low frequencies because its resistance is reduced by the effect of vibration raised at low frequencies.

3.3 Effects of the flow resistance of the absorptive layer in the cavity

The variation of $\alpha-\tau$ due to the change in the flow resistance R_a of the absorptive layer, in the case of a

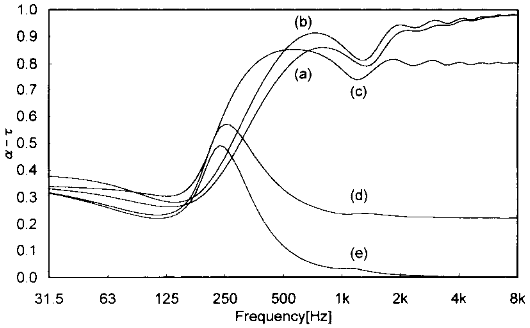

Fig. 5 Effect of the flow resistance Rh of Leaf 1 : Rh=(a) 1.0, (b) 1.0×10^2, (c) 1.0×10^3, (d) 1.0×10^4 and (e) 1.0×10^5 Pa•s/m. The thickness and the flow resistivity of the absorbent in the cavity (placed adjacent to Leaf 1) are 0.05 m and 5.0×10^3 Pa•s/m^2.

double-leaf membrane with a cavity fulfilled by an absorbent, is shown in Fig. 4. The value of $\alpha-\tau$ shows complicated behaviour to the change in R_a, and there are different values of R_a maximising $\alpha-\tau$ at different frequencies. Since the flow resistance R_a is a product of the flow resistivity R_f and the thickness of the layer, there are different combinations of values of R_f and the thickness. Although results are not shown here, further examination has shown that using a thicker material gives higher absorption even if the flow resistivity is smaller, provided that the product, *i.e.*, the flow resistance, is identical.

3.4 Effects of the flow resistance of the permeable leaf, Leaf 1

Figure 5 shows the effects of the flow resistance of Leaf 1 on $\alpha-\tau$ in the case of a double-leaf membrane with an absorptive layer of 0.05 m thick. The values are significantly affected by a change in the flow resistance of Leaf 1, which has also been observed in the case of an air-layer only. The effect is the most significant at high frequencies, and the value of $\alpha-\tau$ shows its maximum in the case (b), which suggests that there is an optimal value maximising $\alpha-\tau$. This optimal value maximising $\alpha-\tau$ has theoretically been derived in the case of a single-leaf permeable membrane.[7)]

3.5 Effects of change in position of the absorptive layer

Although an example is not shown here, the effects of change in position of the absorptive layer, which is of practical interest, was also studied. When the position of the absorptive layer in the cavity changes, it results in a little effect in low frequency range and at frequencies around dips at mid-high frequencies. However, the resultant variation in $\alpha-\tau$ is approximately 0.1 at maximum, even when the layer of 0.05 m thick is placed in various positions in the cavity of total depth 0.6 m. The effect has been found almost negligible, in the case of smaller cavity depth, *e.g.* 0.15 m.

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