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NOISE CONTROL FOR A BETTER ENVIRONMENT

Silencing of the duct noise by using stacked micro-perforated plate with air gaps

Kim, Da-Young[1]
Center for Noise and Vib. Control, Dept. of Mechanical Eng., KAIST
Daejeon 34141, Korea

Ih, Jeong-Guon [2]
Center for Noise and Vib. Control, Dept. of Mechanical Eng., KAIST
Daejeon 34141, Korea

ABSTRACT

Silencing of the mid- to high- frequency noise within a duct can be done by the sound absorbing liner, but the thickness should be large to get an appreciable amount of sound reduction effect. A large amount of sound reduction can be achieved by using the resonance effect of the micro-perforated plate (MPP) with backing cavity. In this work, multiple MPP layers with air gaps in the transverse direction are adopted to widen the effective frequency range. Acoustic impedances of MPP layers is arranged to change gradually to minimize the impedance mismatch. To test the idea, a rectangular duct of 30×30 mm^2 is taken as the main conduit, of which one of the walls is covered with MPP stacks of 9.2 mm in thickness for 0.45 m in length. Transmission loss is estimated by the transfer matrix method. Above 1.7 kHz, TL larger than 5 dB is achieved. The present system is compared with an expansion chamber having same volume and filled with rock wool. It is seen that the proposed system is more effective for 1.1–3.8 kHz range. As a result, a compact silencer for the mid- to high- frequency noise in a duct is designed.

Keywords: Micro-perforated plate, silencer, duct noise, transmission loss.
I-INCE Classification of Subject Number: 35

1. INTRODUCTION

By stacking single MPP layers with air gaps in the transverse direction, it is possible to extend the effective frequency range [1]. There is a possibility that the MPP stack with gradual varying acoustic impedance in the transverse direction can come up with the improvement of the absorbing performance compared to a single MPP with same volume dimension. Also, one can design a compact silencer for the reduction of a wideband noise. This study is a preliminary work on this matter.

2. THEORY

The relative MPP impedance can be expressed as [2]

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[1] d.y.kim@kaist.ac.kr
[2] J.G.Ih@kaist.ac.kr

$$\zeta^{mpp} = r + j\omega m \tag{1}$$

$$r = 32\eta t K_r / \sigma\rho_0 c_0 d^2, \; K_r = \sqrt{1+K^2/32} + \sqrt{2}Kd/(32t), \tag{2a,b}$$

$$\omega m = \omega t K_m / \sigma c_0, \; K_m = 1 + \sqrt{1+K^2/2} + 0.85(d/t). \tag{2c,d}$$

Here, *d* is the hole diameter, *t* the thickness of the MPP plate, σ the porosity, $z_0 = \rho_0 c_0$ the characteristic impedance, $K = d\sqrt{\omega\rho_0 / 4\eta}$ the perforate constant, $\zeta^{mpp} = z^{mpp} / z_0$ the normalized acoustic impedance, and η the dynamic viscosity. The general formulation of the distributed surface impedance of the last MPP that faces the main duct is given by

$$\zeta_0 = z_w / z_0, \; (n=0), \; \zeta_n = \frac{\zeta_{n-1} + \mathrm{j}\tan(kh_n)}{1+\mathrm{j}\zeta_{n-1}\tan(kh_n)} + \zeta^{mpp}_n, \; (n \geq 1). \tag{3a,b}$$

Here, *k* is the wave number, z_w the specific acoustic impedance of rigid wall, h_n the height of the air gap between the *n*th and (*n*-1)th MPP plates, and ζ_n the relative surface impedance in front of the *n*th MPP plate that faces the main duct. The power absorption coefficient α for the normal incidence can be expressed as

$$\alpha = 1 - |R|^2 = 1 - \left|1 - \zeta_n / 1 + \zeta_n\right|^2, \tag{4}$$

where R means the pressure reflection coefficient. The pressure transmission coefficient (T) can be calculated from the four-pole parameters as

$$\begin{bmatrix} p_u \\ U_u \end{bmatrix} = \prod_{i=1}^{N} (\mathbf{LS})_i \begin{bmatrix} p_d \\ U_d \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_T \begin{bmatrix} p_d \\ U_d \end{bmatrix} \equiv \mathbf{T}_T \begin{bmatrix} p_d \\ U_d \end{bmatrix}, \tag{5}$$

where

$$\mathbf{L}_i = \begin{bmatrix} \cos(kl) & \mathrm{j}Z_m\sin(kl) \\ (\mathrm{j}/Z_m)(kl) & \cos(kl) \end{bmatrix}, \mathbf{S}_i = \begin{bmatrix} 1 & 0 \\ A_e / z_0(\zeta_n) & 1 \end{bmatrix}. \tag{6a,b}$$

Here, p denotes the acoustic pressure, U the volume velocity, *u* and *d* the upstream and downstream subscriptions, respectively, Z_m the acoustic impedance of the main duct, A_e the sectional area of the *n*th MPP that is attached to a side wall of the duct, l the spacing between the MPP units, and N the number of segments. With negligible mean flow and assuming a uniform and rigid main duct, the transmission loss (TL) can be obtained as

$$\mathrm{TL} \equiv -20\log_{10}\left(|T|\right) \; \left(\mathrm{dB}\right), \tag{7}$$

where

$$T = 2(T_{11} + T_{12}/Z_m + Z_m T_{21} + T_{22})^{-1}. \tag{8}$$

3. SIMULATION OF ABSORPTION PERFOMANCE

The ratio of the surface impedance between the *n*th and (*n*-1)th layers is defined as $\gamma = \zeta^{mpp}_{n-1} / \zeta^{mpp}_{n}$. Figure 1 shows the absorption performance of the MPP stack when varying γ. The properties of the first MPP layer are *d* = 0.2 mm, *t* = 0.6 mm, and σ = 1.57%. There are three layers of MPP plates and the air gap between the layers is identical as 4 mm. To obtain the absorption coefficient of the stacked MPP unit, a distributed model is used as described in Equation 3. Additionally, a numerical simulation using FEM is conducted to estimate the absorption coefficient $|\alpha|$ using the impedance tube method

[3]. A quadratic Lagrange polynomial is used as a shape function and the maximum mesh size is determined as 8.6 mm considering $\lambda_{\min}/6$, and tetrahedral finite elements are used for the mesh. Equation 1 shows that γ is linearly dependent on ratio of the porosities of MPP, so σ is set to be increased twice as the index of layers, i.e. 1.57, 3.14 and 6.28% for $\gamma = 2$ while σ = 1.57% is only used for $\gamma = 1$. Figure 1 illustrates that $\gamma = 2$ has a higher absorption coefficient >0.7 in a wider range than $\gamma = 1$. This result shows the potential benefits of stacking various MPPs. It can be possible to widen the frequency band of attenuation by modulating the impedance ratio of adjacent MPP layers. In addition, the result using the distributed model and FEM agree will with each other.

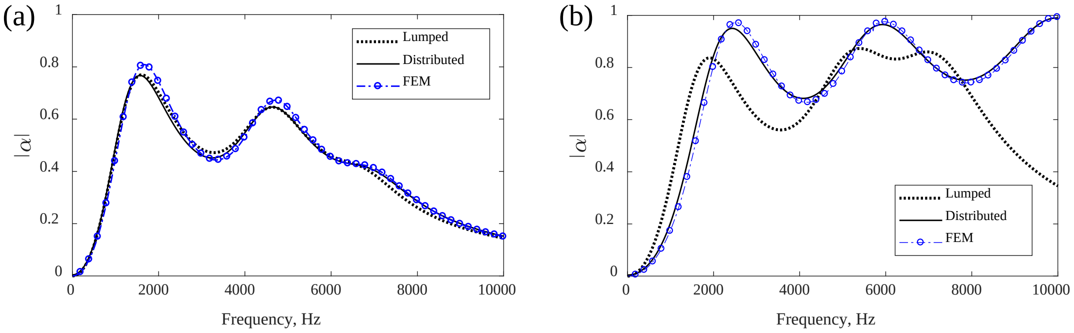

Figure 1. Calculated absorption coefficient of the triple MPP layers for two different impedance ratio variations: (a) γ =1 (constant), (b) γ =2.

4. SILENCING IN A DUCT

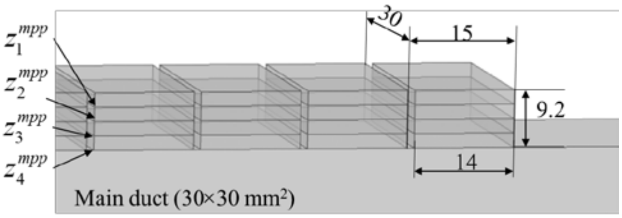

Figure 2. An array of multi-layered MPP stacks attached to a wall of the main duct (units in mm).

Based on the results in Sec. 3, an element using four MPP layers is designed and 30 elements with a 15 mm spatial period are applied in tandem to a wall of the main duct as illustrated in Fig. 2. All heights of the air gaps are same as 2 mm and the total height of the stack unit is 9.2 mm including the thickness of MPP element. Thus, the total treated length is 0.45 m. For the main duct, 30×30 mm^2 is chosen. TL spectrums are analytically evaluated using Equations (5)–(7), and an additional calculation is done by using FEM. It is assumed that the 1 Pa plane wave is incident from the upstream side in the negligible amount of flow. To obtain the TL spectrum, the principle of the three-microphone method [5] is implemented to decompose the incident and transmitted waves. Upstream and downstream observation points are located at 0.056, 0.53, and 0.5 m from the first and last MPP units, respectively. In the first MPP layer, d = 0.2 mm, t = 0.6 mm, and σ_1 = 1.57%. σ_i (i = 1, 2, 3, 4) are selected as 1.57, 1.88, 2.26, and 2.71% for γ =1.2 to achieve the mid- to high-frequency noise reduction. Figure 3(a) exhibits the TL spectrum when the MPP units are used in the wall. A simple expansion chamber of the same volume that is filled with an absorbing material (rock wool, 16 kg/m^3) [6] is also considered for comparison purpose. The result shows that the suggested system is quite effective at 1.1–3.8 kHz band and its maximum level is about 40 dB at 2.6 kHz as shown in Fig. 3.

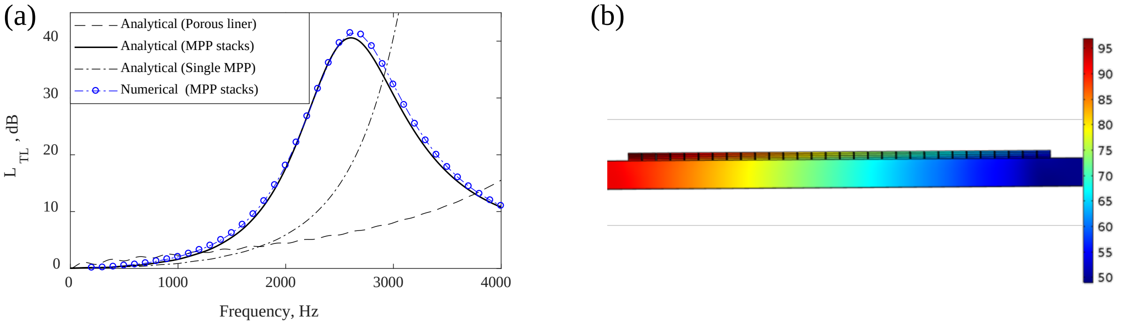

Figure 3.Calculated acoustic performance. (a) A comparison of the transmission losses predicted by three different methods, (b) axial distribution of the sound level in a duct treated with the multi-layered MPP stack (f = 2.6 kHz).

5. CONCLUSIONS

It is shown that the MPP stack with gradually varying acoustic impedance of each MPP layer improves the absorption performance, of which amount is far larger than that of a single MPP or of the porous liner filling the cavity for duct-borne noise reduction. This suggests that the MPP stacks, varying the liner impedance in transverse direction, has a good potential to be used as a compact silencer effective for the mid- to high-frequency wide-band noise reduction. A further study is needed for establishing a design guideline of an optimal selection of the air gaps and impedance ratios. This research can also be extended to the design of a silencer employing the acoustic metamaterial for attenuating the duct-borne noise at low frequencies.

5. ACKNOWLEDGEMENTS

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