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Sound Absorption Enhancement by Thin Multi-Slit Hybrid Structures *

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We report an extraordinary sound absorption enhancement in low and intermediate frequencies achieved by a thin multi-slit hybrid structure formed by incorporating micrometer scale micro-slits into a sub-millimeter scale meso-slit matrix. Theoretical and numerical results reveal that this exotic phenomenon is attributed to the noticeable velocity and temperature gradients induced at the junctures of the micro- and meso-slits, which cause significant loss of sound energy as a result of viscous and thermal effects. It is demonstrated that the proposed thin multi-slit hybrid structure with micro-scale configuration is capable of controling low frequency noise with large wavelength, which is attractive for applications where the size and weight of a sound absorber are restricted.

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For passive noise control, single porosity porous sound absorbing materials have been extensively investigated.[1−3] However, recent studies show that, due to the pressure diffusion effect,[4,5] double porosity materials exhibit improved sound absorption performance relative to single porosity ones. For instance, Sgard *et al.*[6,7] used macro-perforations with scale of centimeters to enhance the sound absorption of porous materials. Gourdon *et al.*[8] added porous inclusions in the macro-perforations to improve the sound absorption of double-porosity media at very low frequencies. More enhancement mechanisms are introduced by embedding inclusions in porous materials, such as multi-component diffraction grating[9,10] and inner resonance.[11] Nonetheless, the aforementioned researches mainly focus on the high permeability contrast situation. The study on double porosity granular materials[12] has considered the low permeability contrast situation, while lacking a thorough insight into the double porosity coupling mechanism. It is known that good sound absorption can be achieved with the help of enough thickness of porous material sheets,[7,12] which directly determines the surface impedance of the sheet. This is due to the fact that the sound absorption of such a sheet at low and intermediate frequencies is dominated by the first sound absorption resonance, which occurs when the sheet thickness is one quarter of the sound wavelength.[13] In this Letter, we demonstrate that the sound absorption of a thin meso-slit structure can be anomalously enhanced at low and intermediate frequencies by introducing micro-slits into the meso-slit matrix to form a new double porosity hybrid structure (Fig. 1).

As schematically shown in Fig. 1, meso-slits with individual slit width W are arranged periodically along the x-direction, while micro-slits with much smaller slit width w are arranged periodically along the y-direction. The solid frame that constitutes the meso- and micro-slits has widths D and d, respectively, and the total thickness of the hybrid structure is s. Consider an incident plane sound wave propagating along the negative direction of the z-axis, with the rigid-backed hybrid structure working as a sound absorber. For illustration, let $W = 0.1\,\mathrm{mm}$, $w = 12.5\,\mathrm{\mu m}$, $D = 0.2\,\mathrm{mm}$, $d = 3.125\,\mathrm{\mu m}$ and $s = 10\,\mathrm{mm}$. In this case, the meso- and micro-slits can be separately regarded as a porous structure having 20% and 80% porosities, respectively, which together compose a double porosity hybrid structure. As assumed by the double-porosity theory, the skeleton of the multi-slit structure is motionless and isothermal, and it is saturated by the compressible Newtonian fluid air. In the considered frequency range, sound wavelength is larger than the size of the largest heterogeneities of the structure, which is the length $W + 2D$ of the unit cell surrounded by red dashed line in Fig. 1. Moreover, the micro-slits and meso-slits are interconnected, the width ratio $w/W = 0.125$ between them is smaller than one, thus the double porosity structure falls into the low contrast category.

First, the acoustic properties of both the meso- and micro-slits are modeled by using the slit theory. For slits of width $2r$ and single porosity φ, the effective density and effective compressibility are given by $\rho = (1/\varphi)\rho_0[1 - \tanh(\sqrt{i}\xi_s)/(\sqrt{i}\xi_s)]^{-1}$ and $C = \varphi[1/(\gamma P_0)]\{1 + (\gamma - 1)[\tanh(\sqrt{i\,\mathrm{Pr}}\xi_s)/(\sqrt{i\,\mathrm{Pr}}\xi_s)]\}$, respectively.[14] Here ω is the angular frequency, ρ_0 is the air density, η is the dynamic viscosity, P_0 is the static pressure of air, γ is the specific heat ratio, Pr is the Prandtl number, $i = \sqrt{-1}$, and $\xi_s = r(\omega\rho_0/\eta)^{1/2}$. By employing the theory for double porosity media,[5] the effective density and

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effective compressibility for the multi-slits of Fig. 1 are expressed as $\rho_{\rm u} = [1/\rho_{\rm e} + (1-\varphi_{\rm e})1/\rho_{\rm i}]^{-1}$ and $C_{\rm u} = C_{\rm e} + (1-\varphi_{\rm e})C_{\rm i}$, where the subscripts i, e and u stand for the micro-, meso- and multi-slits, respectively. The characteristic impedance and propagation constant of the hybrid structure are thence obtained as $Z = (\rho_{\rm u}/C_{\rm u})^{1/2}$ and $\beta = i\omega(\rho_{\rm u}C_{\rm u})^{1/2}$, and the surface impedance is calculated by $Z_{\rm s} = Z\coth(\beta s)$. With sound speed in air denoted by c_0 and the relative impedance defined as $z_{\rm s} = Z_{\rm s}/(\rho_0 c_0)$, the sound absorption coefficient of the rigid-backed hybrid structure is $\alpha = 4{\rm Re}(z_{\rm s})/\{[{\rm Re}(z_{\rm s})+1]^2 + {\rm Im}(z_{\rm s})^2\}$.

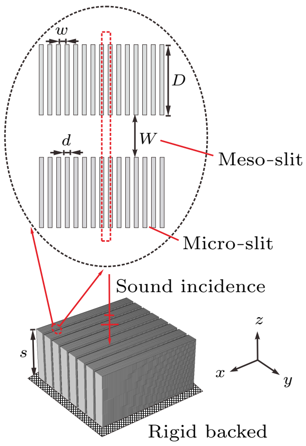

Fig. 1. Schematic illustration of a multi-slit hybrid structure consisting of periodically arranged meso-slits and micro-slits for sound absorption.

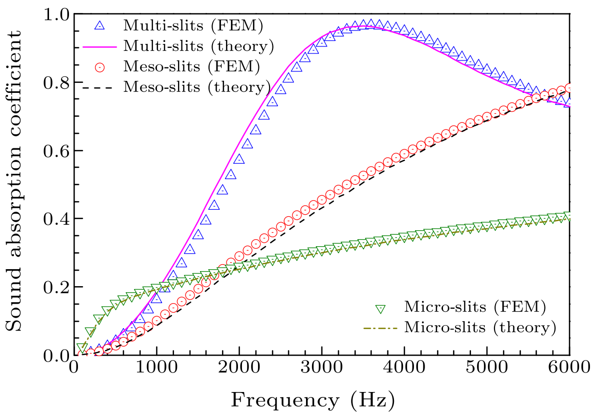

Fig. 2. Sound absorption coefficient of rigid-backed multi-slit hybrid structure under normal sound incidence: Comparison between theoretical model and FEM model, with $W = 0.1$ mm, $w = 12.5$ µm, $D = 0.2$ mm, $d = 3.125$ µm and $s = 10$ mm.

Next, to investigate further the acoustic properties of the hybrid structure, numerical simulations are carried out by using the finite element method (FEM). A periodical FEM model is developed, with periodical conditions exerted on the edges of the unit cell, namely, the rectangular sub-configuration surrounded by the red dashed line in Fig. 1. In the model, the material of the solid frame constituting the multi-slits is taken as non-metal, so that the isothermal boundary condition is imposed at the air-solid interfaces. Assuming a plane sound wave incident on one side of the multi-slit structure that is backed directly with a rigid baffle (Fig. 1), we calculate numerically its effective density and effective compressibility (and thence its sound absorption coefficient) by adopting the experimental-measurement-like method.[15] With $W = 0.1$ mm, $w = 12.5$ µm, $D = 0.2$ mm, $d = 3.125$ µm and $s = 10$ mm, the numerical simulation results are compared in Fig. 2 with those calculated with the double porosity theory. As reference, corresponding results for a meso-slit structure (single porosity 84%) and a micro-slits structure (single porosity 84%) are also presented in Fig. 2: for consistence, their geometrical parameters are identical to those of the multi-slit structure. Good agreement between theoretical predictions and the FEM simulation results is achieved. The results of Fig. 2 demonstrate clearly that, in comparison with either the meso- or micro-slit structure, the proposed multi-slit structure exhibits anomalously enhanced sound absorption over a wide range of low and intermediate frequencies.

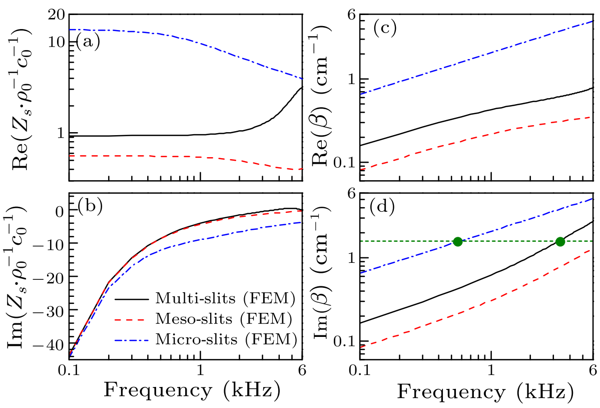

Fig. 3. Real and imaginary parts of surface impedance $Z_{\rm s}$ and propagation constant β.

To gain fundamental insights into the extraordinary performance enhancement as evidenced in Fig. 2, the surface impedance and propagation constant of the multi-slit structure are compared with those of the meso- and micro-slit structures in Fig. 3. According to the theoretical expression for sound absorption coefficient, perfect sound absorption demands zero reactance (${\rm Im}(z_{\rm s}) = 0$) and the resistance equals to that of air (${\rm Re}(z_{\rm s}) = 1$). As shown in Fig. 3(b), the relative reactance ${\rm Im}(z_{\rm s})$ of the multi-slit structure is dominated by the meso-slits, approaching zero much faster than the micro-slits. Further, by mixing the micro-slits into the meso-slit matrix, the relative resistance ${\rm Re}(z_{\rm s})$ of the resulting multi-slit structure approximately equals unity over the low and intermediate frequency range; see Fig. 3(a). Therefore, introducing micro-slits into a meso-slit matrix mainly optimizes the resistance of the meso-slits and has little influence upon its reactance.

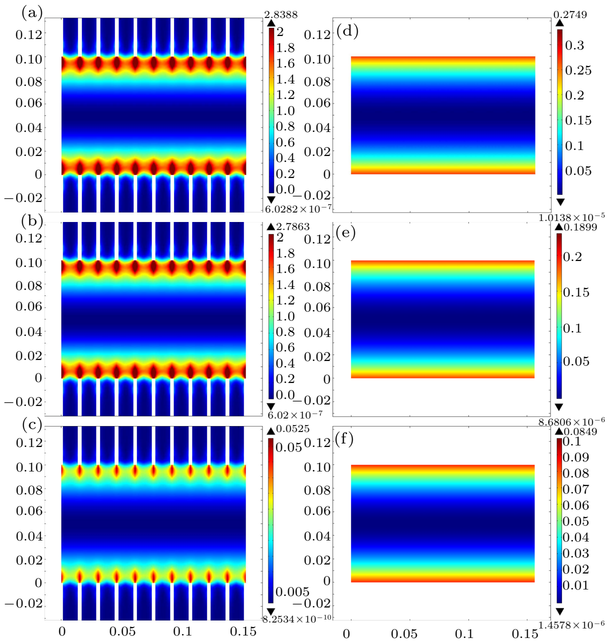

Fig. 4. Comparison of sound energy dissipation between multi-slit hybrid structure and meso-slit structure at 3000 Hz: (a) total thermal-viscous energy dissipation; (b) viscous energy dissipation; and (c) thermal energy dissipation. The abscissa has unit of millimeters, while the ordinate is in W/m^3.

Consider next the propagation constant of the hybrid structure. Combining micro-slits with meso-slits increases significantly both the real and imaginary parts of the propagation constant of the latter; see Figs. 3(c) and 3(d). As is well known, the sound absorption performance of a porous absorber in low and intermediate frequencies is dominated by the first sound absorption peak corresponding to the quarter-wavelength resonance that occurs if $ks = \pi/2$, with $k = \mathrm{Im}(\beta)$ being the sound wavenumber. With the thickness of the hybrid structure fixed at $s = 10$ mm, the first sound absorption peak occurs at $k \approx 1.57\,\mathrm{cm}^{-1}$, which is marked as a horizontal line in Fig. 3(d). As shown in Fig. 3(d), increasing the wavenumber (or imaginary part of the propagation constant) implies that the wavenumber is able to reach the quarter-wavelength resonance wavenumber k at a lower frequency. This is in accordance with the results of Fig. 2. To a large extent, the shift of the sound absorption peak to a lower frequency (relative to the meso-slit structure) results in the remarkable sound absorption enhancement of the multi-slit structure. Although the sound absorption peak of the micro-slit structure appears at a even lower frequency (~500 Hz), its sound absorption capability is poor for its acoustic resistance is far beyond the idealized value of $\mathrm{Re}(z_s) = 1$. As the real part of the propagation constant is actually the attenuation coefficient which increases with decreasing the slit width, the sound wave would attenuate more rapidly in the micro-slits than in the meso-slits. However, the small width (12.5 μm) of the micro-slits leads to high reflection of sound at the incident surface, resulting in poor sound absorption. Nonetheless, the present results demonstrate that incorporating micro-slits into a meso-slit matrix can cause remarkably enhanced sound absorption, which is significant given that the multi-slit structure considered is relatively thin (e.g., $s = 10$ mm).

In contrast to the existing double porosity media proposed for sound absorption where the mesoscopic pores have millimeter scale,[5] the meso-slits considered here have sub-millimeter scale. Whereas mesoscopic pores with millimeter or larger scale can absorb slight sound energy by themselves at low and intermediate frequencies, the present meso-slits with sub-millimeter scale are capable of absorbing a reasonable amount of sound energy (see Fig. 2). Therefore, the sound absorption mechanisms of the proposed double porosity multi-slit structure are completely different to those of existing double porosity media. As is well known, the energy of a sound wave propagating across a porous medium is mainly dissipated within viscous and thermal boundary layers. To explore the mechanisms underlying the remarkable performance of the present multi-slit structure, Fig. 4 compares the numerically predicted sound energy dissipations in the multi-slit structure to those in its meso-slit counterpart. It can be seen from Fig. 4 that energy dissipation in the micro-slits is negligible. However, energy dissipation in the meso-slits is remarkably enhanced as evidenced by the concentration of energy dissipation nearby the junctures of the meso- and micro-slits, which is attributed to the noticeable velocity and temperature gradients induced at these junctures (Fig. 4). Therefore, incorporating micro-slits into a meso-slit matrix to constitute a multi-slit structure leads to significant velocity and temperature gradient distributions, which causes concentration of energy dissipation and hence enhanced sound absorption. In addition, it can be seen from Fig. 4 that the sound absorption is dominated by the viscous effect since the thermal energy dissipation is much less than the viscous energy dissipation in the proposed double porosity multi-slit structure. Note that the thermal dissipation in porous media depends on frequency and wavelength of sound waves.[16] For the relatively high frequency 3000 Hz in Fig. 4, there is not enough time for the occurrence of the thermal conduction between the air and porous frames, which results in a small thermal dissipation in both multi-slits and meso-slits. Due to the shorter wavelength in multi-slits, whose thermal dissipation is inferior to that of meso-slits.

In summary, by introducing micro-slits into a meso-slit matrix, the resulting lightweight multi-slit structure exhibits superior sound absorption performance in low and intermediate frequencies, even if its total thickness is relatively thin. Numerical simulations reveal that the concentration of sound energy dissipation at the junctures of the meso- and micro-slits is responsible for this unusual sound absorption enhancement. The proposed multi-slit structure has promising applications in noise control engineering particularly where the size and weight of a sound absorber are of concern. Further studies are necessary to tailor the performance of the multi-slit structure by systematically varying relevant topological parameters.

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