HIGH-EFFICIENCY SOUND-ABSORBING METASURFACE AT LOW FREQUENCY

Xing-Feng Zhu
Department of Architecture, School of Design and Environment, National University of Singapore, 4 Architecture Drive, Singapore 117566
Jiangsu Key Laboratory on Opto-Electronic Technology, School of Physics and Technology, Nanjing Normal University, Nanjing 210023, China
email: akizhux@nus.edu.sg

Siu-Kit Lau
Department of Architecture, School of Design and Environment, National University of Singapore, 4 Architecture Drive, Singapore 117566
e-mail: slau@nus.edu.sg

Zhenbo Lu
Temasek Laboratories, National University of Singapore, 117411
e-mail: tslluz@nus.edu.sg

Wonju Jeon
Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, South Korea
e-mail: wonju.jeon@kaist.ac.kr

We demonstrate a high-efficiency sound-absorbing metasurface operating at low frequency. The metasurface absorber is based on acoustic porous layer embedded two identical but oppositely oriented split tube resonators. A high absorption (>50%) is obtained in a frequency range from 170 Hz to 750 Hz and over 90% absorption exhibits from 285 Hz to 340 Hz, while the thickness of the absorber is only 1/6 of the relevant wavelength at 500 Hz. The broadband and high absorption performances are due to the coupling of the resonance modes and the trapped mode. Furthermore, the high-efficiency low-frequency absorption of the metasurface is robust under oblique incidence even at large angles. The absorber is ease of fabrication, subwavelength thickness, and robust high-efficiency. Therefore, it has high potential applications in noise control and architectural acoustics.

Keywords: low-frequency sound absorption, broadband, porous material, metasurface

1. Introduction

The attenuation of low-frequency sound waves has long been a challenging issue in the applications of noise control, vibration damping, and sound-screening because of the intrinsically ineffective control by the existing methods [1]. Conventional methods for absorbing acoustic waves rely on the use of porous
and fibrous materials [2-4] or perforated structures with back cavity [5,6], which becomes bulky, heavy-weight and/or less practical for controlling the low frequency sound. Thus, the development of sub-wavelength acoustic absorbers for low-frequency sound is critical. In the past few years, there are considerable efforts to enhance the absorption efficiency by using metamaterials [7-21]. Metasurfaces based on resonators [13-16] are one types of such absorbers which offer an advantages of facile fabrication via three-dimensional (3D) printing. Acoustic metasurfaces demonstrated a very efficient and flexible platform to enhance the sound absorption at low frequencies. However, the sound absorption based on resonators are still in an inherently narrow band because the high absorption would only occur in the vicinity of their resonant frequencies. Therefore, if the absorption band can be widened, the metasurfaces will be useful for the sound attenuation or noise control.

In this paper, we demonstrate the high-efficiency broadband low-frequency acoustic absorption based on resonance metasurface. The unit cell of metasurface is composed of acoustic porous layer embedded two identical but oppositely oriented split tube resonators. This broadband high-efficiency absorption originates from the coupling of the low-frequency resonance mode and the trapped mode. The influence of the incident angle of the plane acoustic wave is further examined by using finite element method to evaluate the broadband and high absorption of the absorber for practical applications.

2. Sound-absorbing metasurface

Figure 1: (a) Cross-sectional configuration of the split tube resonator. (b) The schematic of the unit cell of the sound-absorbing metasurface backed with a rigid wall.

Figure 1(a) illustrates the cross section of the split tube resonator, which consists of two 180°-twisted split rings [19], denoted by SR1 and SR2. The thickness of rings and the width of splits are \( t \) and \( w \). The outer radii of the SR1 and SR2 are \( R_1 \) and \( R_2 \), respectively. Here, the geometric structural parameters are set as \( t = 1 \text{ mm} \), \( w = 1 \text{ mm} \), \( R_1 = 40 \text{ mm} \), and \( R_2 = 25 \text{ mm} \). By embedding the two identical but oppositely oriented split tube resonators (denoted by P1 and P2) into the air-saturated porous layer, the unit cell of the sound-absorbing metasurface is constructed. The inner and the splits of the rings are filled with air. The thickness and length of unit are \( D = 112 \text{ mm} \) and \( L = 188 \text{ mm} \), respectively. The unit cells are arranged periodically along the \( x \) direction and backed by a rigid wall as shown in Fig. 1(b). The air-saturated porous material can be described as a homogeneous effective fluid, which can be modeled by the Johnson-Champoux-Allard model [22]. The effective density \( \rho_e \) and effective modulus \( \kappa_e \) of the porous material can be expressed as
\[
\rho_e = \frac{\rho_0 \alpha_{\infty}}{\phi} \left(1 + i \frac{\omega_v}{\omega} F(\omega)\right),
\]

\[
\kappa_e^{-1} = \frac{\phi}{\gamma P_0} \left(\frac{\gamma - (\gamma - 1) \left(1 + i \left(\frac{\omega_c}{\omega} / (Pr \omega)\right) G(Pr \omega)\right) \phi}{\left(\gamma - (\gamma - 1) \left(1 + i \left(\frac{\omega_c}{\omega} / (Pr \omega)\right) G(Pr \omega)\right) \phi - 1\right)^{-1}}\right),
\]

where \( F(\omega) = \sqrt{1 - i \eta \rho_0 \omega \left(\frac{\sigma_{\infty}}{\sigma \phi \Lambda} \right)^2} \) and \( G(Pr \omega) = \sqrt{1 - i \eta \rho_0 Pr \omega \left(\frac{\sigma_{\infty}}{\sigma' \phi \Lambda'} \right)^2} \) are the correction functions, \( \omega_v = \frac{\sigma \phi}{\rho_0 \sigma_{\infty}} \) is the angular Biot frequency, \( \omega_c = \frac{\sigma' \phi}{\rho_0 \sigma_{\infty}} \) is the adiabatic cross-over angular frequency, \( \rho_0 \) is the density of air, \( P_0 \) is the atmosphere pressure, \( \gamma \) is the specific heat ratio, \( Pr \) is the Prandtl number, and \( \eta \) is the dynamic viscosity of the fluid. The other parameters, porosity \( \phi \), tortuosity \( \alpha_{\infty} \), flow resistivity \( \sigma \), viscous characteristic length \( \Lambda \), thermal characteristic length \( \Lambda' \), thermal resistivity \( \sigma' = 8 \alpha_{\infty} \eta / \phi \Lambda' \), describe the properties of the porous material. Here, the porous material used is polyurethane foam and the acoustic parameters are \( \phi = 0.96, \alpha_{\infty} = 1.07, \sigma = 2843 \text{ Nsm}^{-1}, \Lambda = 273 \mu\text{m}, \) and \( \Lambda' = 672 \mu\text{m} \) [23]. The numerical simulations are performed by using finite element method (FEM) based on COMSOL Multiphysics Version 5.4. As the large impedance mismatch between air and solid materials, we assume that all walls of the split rings are hard boundaries. The mass density and sound speed of the air are \( \rho_0 = 1.21 \text{ kg/m}^3 \) and \( c_0 = 343 \text{ m/s} \), respectively. Perfectly matched layer (PML) is applied in the acoustic domain to model the open boundary condition and Floquet periodic boundary conditions are imposed in the x direction. The incident acoustic plane wave is performed as background pressure field. The amplitude of the incident wave is fixed at 1 Pa.

### 3. Results and discussion

![Figure 2: Absorption coefficient of the sound-absorbing metasurface and acoustic pressure field \( |P/P_0| \) at 218 Hz, 312 Hz, and 570 Hz. \( P_0 \) is the pressure of the incident wave and \( P \) is the scattered acoustic pressure. The blue dotted line and red dashed line show the absorption coefficients of the embedded P1 and P2, respectively.](image)
Figure 2 shows the absorption coefficient of the sound-absorbing metasurface. The absorption coefficient $A$ is calculated as $A = 1 - T - R$, in which $T = |t|^2$ and $R = |r|^2$. The complex transmission coefficient $t$ and reflection coefficient $r$ are retrieved from simulations. For comparison, we also plot the absorption coefficients of the embedded P1 (blue dotted line) and P2 (red dashed line) respectively in Fig. 2. The resonance modes of the P1 and P2 and the trapped mode are close enough to form the coupled modes which keep very broad and large absorption coefficient value. In this case, three absorptive peaks (denoted by a, b, and c in Fig. 2) are found in black line, which correspond to the two resonance absorption peaks and the trapped mode. The absorption coefficient value reaches above 0.5 in a frequency range from 170 Hz to 750 Hz and over 90% absorption exhibits from 285 Hz to 340 Hz. The distribution of the acoustic pressure field $|P/P_0|$ is plotted at the frequencies of 218, 312, and 570 Hz in Fig. 2, corresponding to the absorptive peaks a, b, and c respectively. $P_0$ is the pressure of the incident wave $P$ is the scattered acoustic pressure. The resonance peaks (marked as a and b in Fig. 2) correspond to the maximum of the acoustic pressure located in the split tube resonators. The acoustic pressure distribution at trapped mode frequency (marked as c in Fig. 2) clearly exhibits a maximum on the side of the rigid wall and a minimum on the side of the air, which is typical of a trapped mode.

We further investigate the absorption coefficients of the sound-absorbing metasurface with various width of splits $w$ as depicted in Fig. 3. It can be seen that both the frequency of the resonance absorption peaks and trapped absorption peak increase with $w$ while the absorption performance become better as increasing the $w$ from 1 mm to 3 mm. Thus, the broadband performance of the sound-absorbing metasurface is robust for manufacturing when the width of splits $w$ increases. Furthermore, the influence of the oblique incident angle $\theta$ is investigated for the metasurface in Fig. 4. The incident angle $\theta$ is defined as the intersection angle between the oblique incident waves and the normal direction of the boundary of the porous layer, as shown in Fig. 1(b). It can be seen that the frequency of the absorption peak associated
with the resonant excitation is almost not affected by the variation of $\theta$ because the resonance frequency is not dependent on the excited way of the resonator. The maximum absorption at the resonance frequency is slightly deteriorated at large angles. On the other hand, the frequency of the trapped mode absorption peak increases with $\theta$. That is because the trapped mode frequency increases as the projection of the distance between the resonators and the rigid backing decreases on the wave vector direction for oblique incidence with an angle $\theta$ [24,25]. Increasing incident angle $\theta$ increases the amplitudes of the trapped absorption peaks, which is due to the larger initial absorption of the porous layer. Thus, the broadband absorption is fulfilled in a wide range of incident angle.

Figure 4: Absorption coefficient of the sound-absorbing metasurface at different incident angle $\theta$.

4. Conclusion

A sound-absorbing metasurface has been proposed to achieve high-efficiency absorption for low-frequency sound waves. The unit cell of the metasurface is composed of two identical but oppositely oriented split tube resonators, which are embedded in an acoustic porous layer. A high absorption ($>50\%$) is obtained in a frequency range from 170 Hz to 750 Hz and over 90% absorption exhibits from 285 Hz to 340 Hz, while the thickness of the absorber is only $1/6$ of the relevant wavelength at 500 Hz. The broadband and high absorption performances are due to the coupling of the resonance modes and the trapped mode. In addition, the high-efficiency low-frequency absorption of the metasurface is robust when the width of splits $w$ changes and oblique incidence even at large angles. The absorber is ease of fabrication, subwavelength thickness, and robust high-efficiency. Therefore, it has high potential applications in noise control and architectural acoustics.
5. **Acknowledgements**

The authors wish to acknowledge the funding support by the Singapore’s Ministry of Education Academic Research Fund Tier 1 (WBS R-295-000-157-114) and the National Natural Science Foundation of China (11704193).

6. **References**