SOUND ABSORPTION USING A TWO-SCALE CHECKER-BOARD META-SURFACE WITH MICRO HELMHOLTZ RESONATORS

Hyeonbin Ryoo and Wonju Jeon

Department of Mechanical Engineering, Korea Advance Institute of Science and Technology (KAIST), 34141, Daejeon, Republic of Korea
email: rhb9306@kaist.ac.kr

In this study, we propose an acoustic meta-surface consisting of Helmholtz resonators in sub-wavelength scales for the purpose of absorbing the acoustic wave with two distinct frequencies. The meta-surface has a checkerboard pattern of two unit modules: the first unit module has four Helmholtz resonators of two types (A1, B1), and the second unit module has four Helmholtz resonators of two types (A2, B2). We obtain approximately 80% of sound absorption for each frequency, and derive a user-friendly mathematical formula for the practical design of sound absorber. In addition, we propose a modified geometry of meta-surface to minimize the total reflectivity when the incident wave has different amplitude for each frequency.
Keywords: sound absorption, Helmholtz resonators, acoustic meta-surface

1. Introduction

A challenging issue on perfect sound absorber with subwavelength scale has attracted a great deal of interest from engineers. To design a perfect sound absorber, not only the surface of the absorber has an impedance matched with background medium, but also there is an appropriate mechanism to convert acoustic energy such as viscous or thermal losses. Recent researches [1-5] reported that acoustic metamaterial could be used to design almost perfect absorber at certain frequencies.

As a type of sound absorber, the research on meta-surface using Helmholtz resonators has rapid progress due to their ease of fabrication [2-5]. By using the concept of coiled space, recent researchers [2,3] achieved experimentally or numerically high absorption coefficient at a resonance frequency with very thin panels. On the other hand, in 2016, Li *et al.* [4] designed a nearly perfect absorber with a thickness of $\lambda/20$ by using the coupled effect of two Helmholtz resonators that have 180° phase difference. In the numerical simulation, they treated the effects of thermal and viscous losses of sound in air by introducing an imaginary part of sound speed. In the same year, Jimenez *et al.* [5] proposed a meta-surface for quasi-omnidirectional sound absorption with a thickness of $\lambda/88$. The main idea of their work were to manipulate the slow speed of sound and to use the concept of critical coupling. In addition, they used the viscous-thermal losses model of previous work [6] to understand sound absorption in very narrow regions.

However, the previous works on sound absorbing meta-surface using Helmholtz resonators have their objectives at enhancement of absorption coefficient at one frequency. Thus, in this work, we propose an acoustic meta-surface with multiple Helmholtz resonators for sound absorption at two distinct frequencies. In addition, we validate the proposed design theoretically and numerically by using effective complex and frequency dependent material properties (ρ_{eff} and κ_{eff}).

In Section 2, we describe the geometry of proposed meta-surface. In Section 3, we briefly state viscous-thermal losses model. In Section 4, the numerical results of proposed meta-surfaces for the sound absorption at two different frequencies. In Section 5, the conclusion will be stated.

2. Two-Scale Meta-surface and Visco-Thermal Losses Model

In this section, we briefly describe the geometry of proposed meta-surface and state the visco-thermal losses model by using effective complex material properties depending on the frequencies of incident waves and the geometries of resonators. For achieving sound absorption at two different frequencies, we propose two-scale checkerboard meta-surface with multiple Helmholtz resonators. The whole panel is periodically composed in two directions (x-direction and y-direction) by multiple unit cells. A unit cell contains four modules with two different types: unit module 1 and unit module 2. Then, each unit module has four Helmholtz resonators with two different types: A1 and B1 for unit module 1 and A2 and B2 for unit module 2, respectively.

As reported by Stinson [6], the propagation of sound in narrow tubes can be theoretically solved by using the effective material properties. For the square cross-sectional ducts (necks of Helmholtz resonators), the effective density ρ_{eff} and the effective bulk modulus κ_{eff} can be written by:

$$\frac{\rho_{eff}(\omega, w)}{\rho_0} = -\frac{\mu w^4}{4i\rho_0\omega \sum_{k\in \boldsymbol{N}} \sum_{m\in \boldsymbol{N}} \left[\alpha_k^2\beta_m^2\left(\alpha_k^2+\beta_m^2-\frac{i\omega\rho_0}{\mu}\right)\right]^{-1}}, \quad (1)$$

$$\frac{\kappa_{eff}(\omega, w)}{\kappa_0} = \frac{w^4\mu}{\gamma\mu w^4 + 4(\gamma-1)iPr\rho_0\omega \sum_{k\in \boldsymbol{N}} \sum_{m\in \boldsymbol{N}} \left[\alpha_k^2\beta_m^2\left(\alpha_k^2+\beta_m^2-\frac{i\omega Pr\rho_0}{\mu}\right)\right]^{-1}}, \quad (2)$$

for $i = 1, 2, 3, 4$, where ω is the angular frequency of incident wave, w is the width of square necks of Helmholtz resonators, ρ_0 is density, κ_0 is bulk modulus, γ is specific heat ratio, μ is the dynamic viscosity, and Pr is Prandtl number. Here, the constants α_k and β_m are defined as $\alpha_m = 2(k+1/2)\pi/a$ and $\beta_m = 2(m+1/2)\pi/b$, respectively. As shown in Eqs. (1) and (2), the effective complex density and bulk modulus are functions of the angular frequency ω and geometrical parameter w (width of the necks of Helmholtz resonators). According to the Ref. [6], this model is valid when the following conditions are satisfied:

$$w_i > 10^{-3}\ [cm] \quad (3)$$

$$w_i f^{\frac{3}{2}} < 10^6\ [cm\ s^{-\frac{3}{2}}] \quad (4)$$

for $i = 1, 2, 3, 4$, where f is the frequency $(= \omega/2\pi)$.

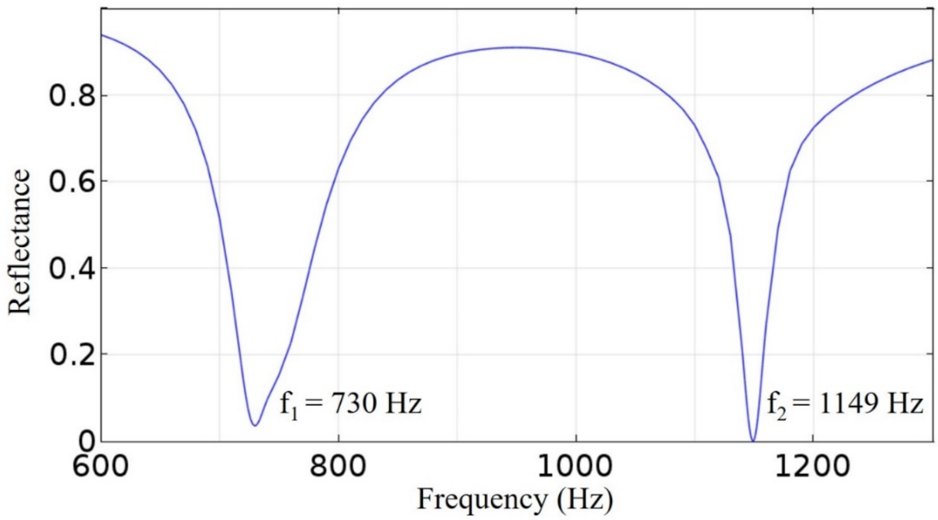

Figure 1: Reflectance from the proposed meta-surface.

3. Results and Discussions

In this section, the numerical analysis for absorption coefficient of two-scale checkerboard meta-surface is performed by using the effective material properties. The simulations are performed by using Pressure Acoustics module of commercial software COMSOL Multiphysics. The material properties of air are set as follows: $\rho_0 = 1.21\ [kg/m^3]$, $\kappa_0 = 142\ [kPa]$, $\gamma = 1.4$, $\mu = 1.56 \times 10^{-5}\ [Pa \cdot s]$ and $Pr = 0.707$. Since walls of Helmholtz resonators have extremely larger characteristic impedance than the air, the walls are assumed to be acoustically rigid boundaries.

Figure 1 shows the reflectance of proposed meta-surface impinged by incident wave with frequency range of $600\ [\text{Hz}] < f < 1300\ [Hz]$. Note that the geometrical parameters and calculated frequency range satisfy Eqs. (3) and (4). As shown in Fig. 1, more than 95% of sound energy is absorbed and converted other types of energy at two different frequencies of 730 Hz and 1149 Hz.

4. Conclusion

We proposed a two-scale checkerboard acoustic meta-surface made up by multiple Helmholtz resonators in sub-wavelength scales, for the purpose of sound absorptions at two distinct frequencies. By using the effective complex material properties depending on frequency and geometrical parameters [6], we numerically validated the proposed meta-surface. As a result, over 95% of sound energy was converted to other forms of energy at two distinct frequencies. Further, we can derive the user-friendly mathematical formula for the practical applications. In addition, we may propose how to modify the geometry for multiple waves with different amplitudes and frequencies.

REFERENCES

1 Mei, J., Ma, G., Yang, M., Yang, Z., Wen, W. and Sheng, P., Dark acoustic metamaterials as super absorbers for low-frequency sound, *Nature Communications*, **3**, 756, (2012).

2 Cai, X., Guo, Q., Hu, G. and Yang, J., Ultrathin low-frequency sound absorbing panels based on coplanar spiral tubes or coplanar Helmholtz resonators. *Applied Physics Letters*, **105** (12), 121901, (2014).

3 Li, Y. and Assouar, B. M., Acoustic metasurface-based perfect absorber with deep subwavelength thickness, *Applied Physics Letters*, **108** (6), 063502, (2016)

4 Li, J., Wang, W., Xie, Y., Popa, B. I. and Cummer, S., A sound absorbing metasurface with coupled resonators, *Applied Physics Letters*, **109** (9), 091908, (2016).

5 Jiménez, N., Huang, W., Romero-García, V., Pagneux, V. and Groby, J. P., Ultra-thin metamaterial for perfect and quasi-omnidirectional sound absorption. *Applied Physics Letters*, **109** (12), 121902, (2016).

6 Stinson, M. R., The propagation of plane sound waves in narrow and wide circular tubes, and generalization to uniform tubes of arbitrary cross-sectional shape, *Journal of the Acoustical Society of America*, **89** (2), 550-558, (1991).