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Honeycomb-shaped meta-structure for minimizing noise radiation and resistance to cooling fluid flow of home appliances

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ABSTRACT

Meta-structures composed of honeycomb-shaped unit cells were built to have high sound-proof and heat-exhaust performance. Each unit cell operates as a Helmholtz resonator (HR) and a lumped inertance muffler (LIM), resulting in sound energy dissipation at specific tonal and broadband frequencies and minimal noise transmission. This cover structure allowed heat-exhaust through the open cross-sectional area. The acoustic characteristics of the meta-structure fabricated using ABS were measured by the four microphone method. The bandgap at specific frequencies and noise reduction at high frequencies were investigated. The significant change of negative effective mass density and the purely complex value of the wave speed were measured at the resonant frequency band of HR. The theoretical model was suggested to analyze the noise reduction mechanism. The designed meta-structure was applied as the covers of the refrigerator machine room and the top-loading washing machine for demonstrating a practical noise control applications. The suggested structures were designed to meet same geometric constraints as the original cover both in dimensions and open area for heat exhaust. To evaluate the noise reduction performances, the sound radiations from the operating refrigerator and washing machine were measured. The noise transmitted through the panel was significantly reduced by using the proposed cover in the specific frequency bands. For the washing machine, the efficiency depended on the type of the operating process. Noise reduction was large during the fill and wash process, whereas, minimal during drain and spin process. Because the resonance and cut-off frequencies of HR and LIM were designed as 570 and 300 Hz, respectively, the effectiveness was minimal for low frequency sounds. The temperature of the operating compressor of refrigerator and the spinning motor of washing machine showed minimal increase suggesting identical heat exhaust performances. The suggested meta-structure induced large noise reduction without influencing heat exhaust by similar open area for fluid flows as the original cover.

1. Introduction

The acoustic metamaterials are artificial creation of a structure to exhibit arbitrary physical properties using local resonance or scattering in a periodic arrangements. The objective in this paper is to create material having superior noise control performance in a specific frequency ranges that was not possible before using conventional porous structures. The periodic structure – Phononic crystal is composed of a non-homogeneous medium arranged in a three or two-dimensional matrix. Primary performance of a noise control material is to block sound generated inside a machine without sacrificing operation efficiency.

Acoustic metamaterials have been suggested for several wave control applications. A lattice periodic system composed of mass-in-mass unit cells shows the bandgaps of negative effective mass density at specific frequencies [1–3]. The rectangular or hexagonal distribution of particles [4,5] was utilized for this wave control. Membrane type resonator having centered mass was proposed for dissipation of incident sounds [6,7]. Serial acoustic resonators exhibited acoustic wave control [8,9]. Conventional sound absorption materials exhibit low effective permeability. For application to noise control of the systems with motors and compressors, the low flow resistance structure to airflow for cooling is important for high performance. In view of this point, heat exhausting but sound proof acoustic meta-structure was proposed by the authors [10].

The tonal and broadband noises were mostly caused by fans, compressors, and motors in digital appliance. These types of noise degrade the perceived quality for the products. The perceived

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acoustic quality has an influence on the customer selection. The Consumer Reports [11] grades the products through perceived assessment in North America, and STIWA [12] marks the noise level of a product to determine sales price in Europe. In this paper, a meta-structure panel composed of honeycomb-shaped unit cells having high performance of sound-proof and heat-exhaust for noise control was suggested. The suggested panel showed strong noise reduction capability using sub-wavelength devices without using the physically air-blocking structure. It has open areas for flow exit to enable heat-exhaust. Each unit cell operates as a Helmholtz resonator and a lumped inertance muffler, resulting in sound energy dissipation at specific tonal and broad band frequencies. Impedance tube method was used to measure acoustic material properties. Theoretical model for the meta-structure was suggested for analyzing the noise reduction mechanism. Designed panel was applied in the machine room of a refrigerator and the frame of the top loading washing machine to analyze the noise reduction and heat exhaust capability and was compared with the original cover to verify the noise reduction capability.

2. Design and fabrication

The sound-proof and heat-exhaust meta-structure panel composed of honeycomb-shaped unit cell was designed and fabricated. Fig. 1(a) and (b) are schematic diagrams of the designed meta-structure viewed from the inlet and outlet side. The heat fluxes passed through the exhaust hole located in the middle of the unit cell. The sound was reduced due to the Helmholtz resonator (HR) and the lumped inertance muffler (LIM). When each resonator unit operates at tuned frequencies, the incident acoustic wave is blocked from transmission. It creates band gap frequencies preventing sound transmission. The LIM unit reduces sound transmission for the broadband noise. To maximize the effective permeability, HR neck was placed at the end of the exhaust cylinder as shown in the Fig. 1(c). For maximizing the noise reduction capability when applied to the refrigerator considered in this study, resonance and cut-off frequencies of HR and LIM were designed as 570 and 300 Hz, respectively (V_h, the cross-sectional area, S_h, the length of the neck of HR, L_h, and the cross-sectional area of LIM, S_p, were 10,981 mm^3, 7.1 mm^2, 4.0 mm, and 133 mm^2, respectively). The lattice constant, a, was designed as 29.7 mm.

3. Analysis of the sound transmission through meta-structure

3.1. Wave propagation at the meta-structure

When the plane wave propagates through meta-structure shown in the Fig. 1(d), according to the boundary conditions at $x = 0$, the reflected (B_1) and transmitted (A_2) amplitudes are related to the acoustic impedances as

$$A_1 + B_1 = A_2, \quad (A_1 - B_1)/z_1 = A_2/z_2 \tag{1,2}$$

where $z_1 = \rho_0 c_0/S_1$ is the acoustic impedances at the inlet and S_1 is the cross-sectional area of inlet. z_2 is the total acoustic impedance of the designed meta-structure. A_1 is the amplitude of incident wave. The acoustic impedance of the unit cell was analyzed to predict the acoustic characteristics of parallelly arranged meta-structure with honeycomb-shaped unit cells. Fig. 1(c) shows the section drawing of unit cell and the wave propagation characteristics. The total acoustic input impedance of unit cell, z_2, is calculated as

$$z_2^{-1} = z_h^{-1} + z_s^{-1} \tag{3}$$

where z_h, and z_s are the acoustic impedance of the HR and the LIM, respectively. The acoustic impedance of the Helmholtz resonator, z_h, was given as [13]

$$z_h = \frac{1}{S_h^2}\left[R_w + \frac{\rho_0 c_0 k_0^2 S_h^2}{2\pi} + j\left(\omega\rho_0(L_h + 1.4a_h)S_h - \frac{\rho_0 c_0^2 S_h^2}{\omega V_h}\right)\right] \tag{4}$$

where ρ_0, c_0, and k_0 are the mass density, sound speed, and wavenumber of air and R_w is the viscous loss of rigid wall expressed

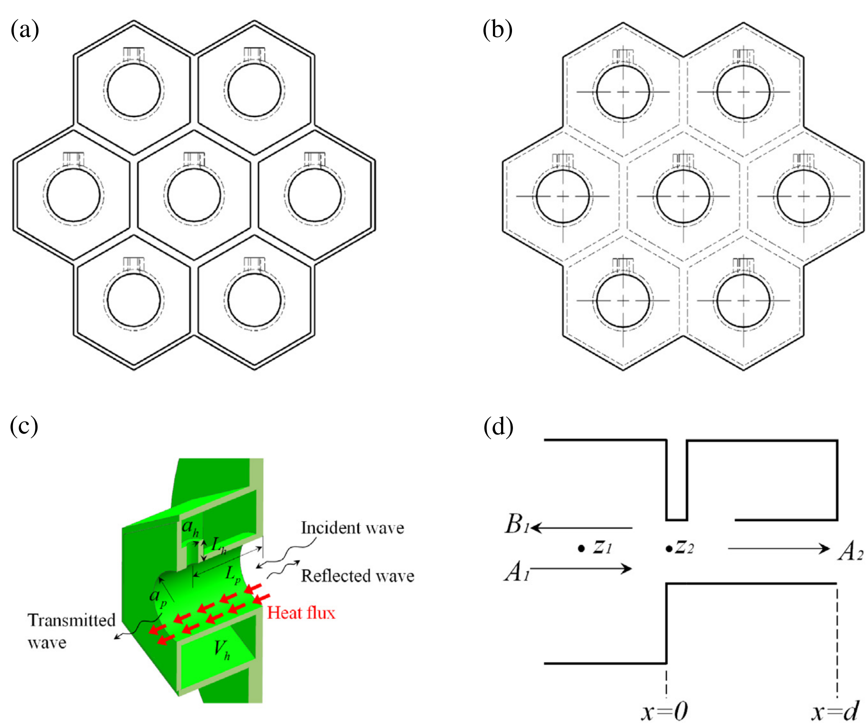

Fig. 1. Designed meta-structure panel: (a) flow inlet and (b) outlet of the panel, (c) wave propagation and fluid flow through a unit cell, and (d) the schematic diagram.