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Air transparent soundproof window

Sang-Hoon Kim[1,a] and Seong-Hyun Lee[2]
[1]*Division of Marine Engineering, Mokpo National Maritime University, Mokpo 530-729, R. O. Korea*
[2]*Korea Institute of Machinery and Materials, Yuseong-Gu, Daejeon 305-343, R. O. Korea*

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A soundproof window or wall which is transparent to airflow is presented. The design is based on two wave theories: the theory of diffraction and the theory of acoustic metamaterials. It consists of a three-dimensional array of strong diffraction-type resonators with many holes centered on each individual resonator. The negative effective bulk modulus of the resonators produces evanescent wave, and at the same time the air holes with subwavelength diameter existed on the surfaces of the window for macroscopic air ventilation. The acoustic performance levels of two soundproof windows with air holes of 20mm and 50mm diameters were measured. The sound level was reduced by about 30 - 35dB in the frequency range of 400 - 5,000Hz with the 20mm window, and by about 20 - 35dB in the frequency range of 700 - 2,200Hz with the 50mm window. Multi stop-band was created by the multi-layers of the window. The attenuation length or the thickness of the window was limited by background noise. The effectiveness of the soundproof window with airflow was demonstrated by a real installation. [http://dx.doi.org/10.1063/1.4902155]

I. INTRODUCTION

Electromagnetic waves are transverse waves and do not need any medium to travel. On the other hand, sound waves are longitudinal waves and need a medium to travel. Sound is embedded into the medium by pressure, therefore, it is not surprising to believe that the medium and sound cannot be separated. For acoustic transmissions most previous works were many-holed plates or large transmissions at specific frequency ranges.[1–4] A few groups focused on a combination of macroscopic ventilation and soundproofing. Microperforated panels (MPP) have been used widely as absorbing materials since the 1960s.[5] The ratio of the perforation radius to the viscous boundary layer thickness inside the hole is a key factor affecting sound absorption.

Soundproofing using the high absorbing characteristics of MPP was demonstrated by Garcia-Chocano et al.[6,7] They used a specially designed array of cylindrical columns or sonic crystals using MPP, and their principle is based on multiple scattering phenomena at the surfaces of absorptive units. Those layered structures could have the visibility limit, and thus are suitable for acoustic barriers rather than windows. For ventilation and soundproofing together, parallelepiped units were introduced by Yuya et al.[8,9] They used a large rectangular cube with input and output openings at both ends, but the attenuation was on order of only 10dB. In spite of those studies, an anti-transmission that allows a medium to pass through a holed structure but blocks the sound effectively has not been studied very much.

In recent years the research on acoustic transmission has accelerated due to the rapid development of acoustic metamaterials. Metamaterials are artificial structures consisting of subwavelength units with dynamical properties not available in nature. In electromagnetism, electric permittivity and magnetic permeability are the two fundamental parameters characterizing the electromagnetic

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[a] Electronic mail: shkim@mmu.ac.kr.

property of a medium. These two parameters describe how a field affects and are affected by a medium. Light and sound share many important wave characteristics. In acoustics, modulus and mass density are the two counterparts characterizing the mechanical property of a medium. Negative parameters are in the center of metamaterial research. Similarly to electromagnetic metamaterials, resonance is the key to create effective negative response in acoustic metamaterials. Double negative parameters produce a backward wave, and single negative parameter produces an evanescent wave.[10] The conversion to the evanescent wave is the road to soundproofing.[11]

The separation between medium and sound has been successfully demonstrated. The key is the Helmholtz resonators or its applications.[12–15] It makes the effective bulk modulus of the medium negative. It is not a new system, but a new interpretation of the acoustic resonance and has been applied to a mechanical system such as a muffler for a long time. With the help of a modified Helmholtz resonator and the muffler principle, we designed a soundproof window or wall where air is allowed to flow freely within some specific frequency ranges. A numerical simulation by computer was performed before making the experiments. We discuss the most effective soundproof conditions allowing maximum airflow. Recently an experiment of 'sound transparent airproof wall' was reported.[13] The air transparent soundproof window is the reverse procedure of the experiment.

II. THEORY

There are two conditions for a soundproof window where air passes through freely. The first condition is strong diffraction. It makes the wave diffuse into the resonator According to Huygen's principle, every point of a wave front acts as a source of a secondary wave that spreads out in all directions. The envelope of all the secondary waves is the new wave front. A common bottle-type Helmholtz resonator is not suitable for the purpose. Therefore, we designed another resonator of an acoustic cell and called it a *diffraction resonator*. It is shown in Fig. 1. It has an air hole in the center of its body to maximize the diffraction effect. When the wavelength of the incoming wave is much larger than the size of the holes, it will be diffracted strongly into the holes.

Three different cells were designed. A cell is composed of one, two, or four rooms, and each room works as a resonator. The air hole and the rooms are separated by an air filter to match the acoustic impedance. The air filter is a dissipative material for sound and the acoustic impedance $z = \sqrt{\rho B}$ is frequency dependent in general. Therefore, air filter with variable impedance affects the dissipation label. For example, if this impedance is different a lot from the one of the air, most of the energy will be directly reflected at the upwind end of tube. However, when we installed an automotive air filter (P = 280 ± 20mm Aq) for impedance matching, there was little difference in the transmission loss between with and without it.

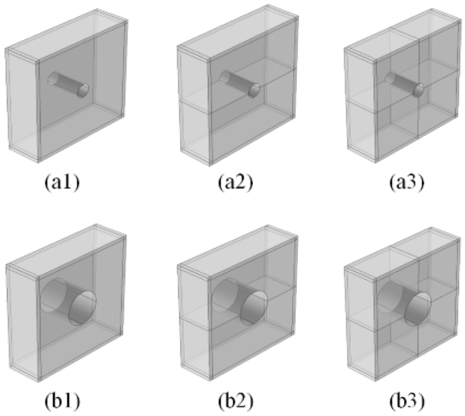

FIG. 1. Diffraction resonators or acoustic cells. Diameters of the air holes: 20mm for (a1), (a2), and (a3), and 50mm for (b1), (b2), and (b3). There are three structures: one room for (a1) and (b1), two rooms for (a2) and (b2), and four rooms for (a3) and (b3).

The cell is made of transparent acrylic with a thickness of 5mm. The inner dimension of each cell is 150mm × 150mm × 40mm, and the diameters of the air holes are 20mm and 50mm. Afterwards, we composed the cells in parallel and series to construct a window or a wall. This method is different from a perforated sheet or acoustic pipes of low-pass filters.[16] The diameter D of the air hole of the cells should be much smaller than the wavelength, λ, of the applied sound wave for strong diffraction. Therefore, the upper limit of the soundproof frequency is restricted by the diffraction condition

$$f < f_c, \tag{1}$$

where f_c is the cutoff frequency of the strong diffraction.

The second condition is the negative bulk modulus of the resonators that attenuates the acoustic wave. Acoustic waves are created by compressibility or elasticity of the medium. Youngs modulus is a one-dimensional compressibility, shear modulus is a two-dimensional one for a surface wave, and bulk modulus is a three-dimensional one, but in principle they are identical. The bulk modulus B is defined by $\Delta P = -B\Delta V/V$, where P is the pressure and V is the volume. The speed of an acoustic wave in fluid depends on the fluids compressibility and inertia. If the fluid has the bulk modulus B and an equilibrium mass density ρ, then the speed of sound in it is $v = \sqrt{B/\rho}$. The resonance of accumulated waves in the resonator reacts against the applied pressure at some specific frequency ranges. That is, it creates $\Delta V > 0$ and, then, $B < 0$ effectively. The negative modulus is then realized by passing the acoustic wave through the resonators. This principle is the same with muffler's. By this procedure the amplitude of the sound wave is attenuated exponentially. This is the fundamental mechanism of the attention of acoustic waves by the effective negative bulk modulus.

The general form of the effective bulk modulus, B_{eff}, of acoustic waves is given by the complex form similar to the effective electric permittivity in electric metamaterials[12,14,15,17,18]

$$B_{eff}^{-1} = B^{-1}\left[1 - \frac{F\omega_o^2}{\omega^2 - \omega_o^2 + i\Gamma\omega}\right], \tag{2}$$

where ω_o is the resonance frequency, Γ is a loss by damping, and F is a geometric factor. We plotted the real and imaginary part of the effective modulus in Fig. 2. The negative range of the real part is the stop-band of the wave.[19] The acoustic intensity decays at the frequency range. When the loss is small, the effective bulk modulus has a negative real value at the frequency range

$$f_o < f < \sqrt{1+F}\, f_o, \tag{3}$$

where $f_o = \omega_o/2\pi$. The soundproof range depends on the magnitude F. The F is the ratio of the volume of the resonator compared with the volume of the air passage,[12] and is estimated by a combined method of theory and experiment. An acoustic pressure drop by a resonant window in a specific frequency is shown in Fig. 3 by numerical simulation.

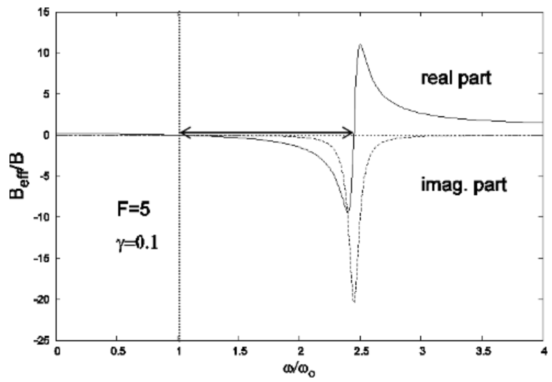

FIG. 2. A typical plot of effective modulus around resonance. The arrowed region of the frequency has negative real part. $\gamma = \Gamma/\omega_o$.

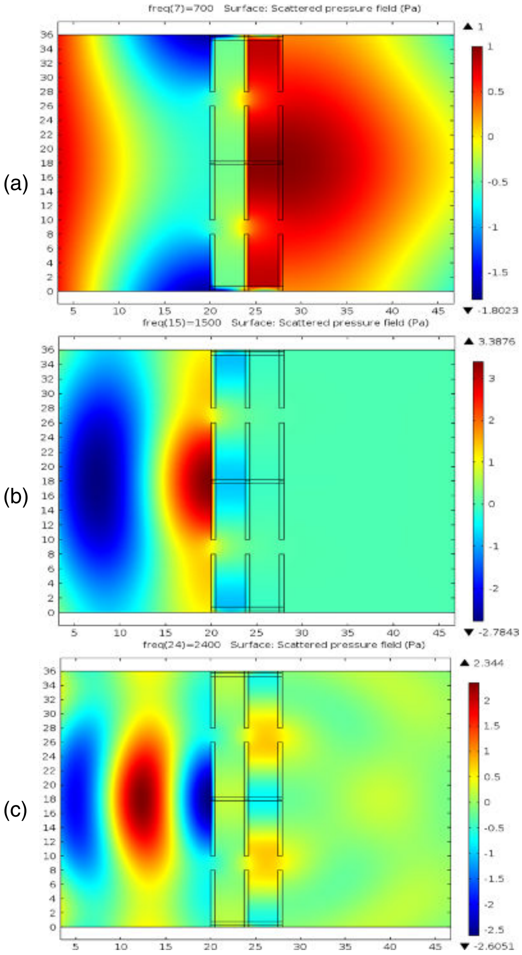

FIG. 3. Numerical simulation of acoustic pressure by double layered diffractions resonators. (a) f=700Hz, (b) f=1,500Hz, and (c) f=2,400Hz. There is little attenuation at low and high frequencies, and a serious attenuation at the intermediate frequency.

For the soundproof with air flow, the two conditions of Eq. (1) and Eq. (3) must both be satisfied. The smaller air hole and lower resonant frequency guarantee the wider frequency range of soundproofing. The larger air hole helps to pass through the air without losing the pressure but it lowers the cutoff frequency. Therefore, the optimization condition of least sound and maximum airflow is

$$\sqrt{1+F}\, f_o = f_c. \tag{4}$$

The larger air hole helps the air to pass through without a loss of acoustic pressure, but it lowers the cutoff frequency f_c. The amount of air flow is proportional to the air pressure drop caused by the window.

It is clear that there is strong reflection in the surface of the window from Fig. 3. Besides the effective modulus, the effective density inside and outside of the resonator is different, and it makes the air pressures at the two ends of the air hole in-phase or out-of-phase. Then, it creates multiple modes of resonances.[20,21] The resonance frequency f_o in Fig. 2 is just the lowest one among the multi-modes. Therefore, we have to consider every possible mode of the resonance frequencies for multiple stop-bands. It is difficult to define a single cutoff frequency because each stop-band has each cutoff frequency. The f_c in Eq. (4) is the lowest one for the strong diffraction, but the relation is practically useful when we design a real model.[21]

Around the resonance frequency, the particle velocity in the air hole becomes very large, but the inertia of the fluid always accompanies with resonance.[18] Therefore, the entrance displacement

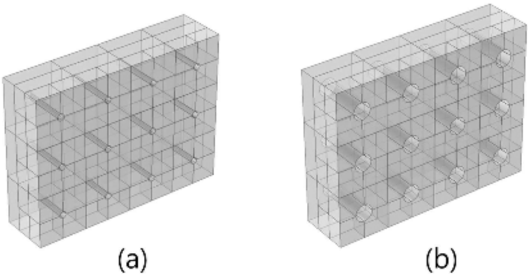

FIG. 4. Designs of the medium-sound separator. (a) 20mm and (b) 50mm. It is composed of the three kinds of cells which are connected in series and parallel positions.

of the air hole is deformed by pressure to opposite directions and it produces a negative effective density. The combination of negative effective density and negative effective bulk modulus produces a backward flow.[22] The double negative region still produces a stop-band but makes a noise for the window.

III. EXPERIMENT

The sample soundproof window has an array of $3 \times 4 \times 3$ cells arranged in parallel and series positions as shown in Fig. 4. We connected three pieces of the cells in Fig. 1 in a series. The first piece has one chamber, the second one has two rooms, and the third one has four rooms. The large volume or small entrance area of the room correspond to the low resonant frequency. Using this structure, the window has three different stop-bands. The 20mm window in Fig. 4(a) is designed to measure background noise level of complete soundproofing while the 50mm window in Fig. 4(b) serves the practical purpose of noise reduction.

The minimum length of the air passage for the soundproofing is obtained from the imaginary wave-vector. The amplitude of the plane wave attenuates via $e^{ikx} = e^{-2\pi|n|x/\lambda}$, where $|n|$ is the refractive index in the cell and close to 1. For the attenuation of the amplitude of $1/e$, the length of the air passage is $x = \lambda/2\pi$. The thickness or total pure length of the air passage of the windows is $40\text{mm} \times 3 = 120\text{mm}$. Large imaginary wave-vector gives evanescent waves with smaller decay length, hence has better effects in sound blocking. Even for small imaginary wave-vector, it is not necessary for the soundproof to be too long space because the dissipated energy creates resonating sound in the resonators such as hearing the call of the conch on the beach as a background noise. For the waves of higher than 500Hz, the attenuation length of order of 10cm is good enough for satisfactorily soundproofing in real installation. However, for the waves of lower than that frequency, we need more space for the attenuation. The thickness of the window could be very thin if a curved air passage is used.[23]

The measurement of the sound transmission loss using small chambers was carried out in accordance with the test standards for large reverberation chambers: ISO 10140:2010 and ASTM E 90:2004. The test facility, called a 'mini-chamber', consists of two adjacent reverberant chambers with a test opening between them in which the test specimen is inserted. (a) area of the specimen: W 1.2m × H 1.0m, (b) volume of Source Room: $2.808m^3$, and (c) volume of Receiving Room: $3.252m^3$.

The distance between the emitters and the window is 1,200mm, and the distance between the receiver positions and the window ranges from 200 to 1,100mm. Kang et al. studied the characteristics of sound insulation in the mini-chamber.[24] The shape of the chamber is designed to be irregular in order to avoid the occurrence of standing waves. Two speakers (JBL, CONTROL 1X) containing a half-inch high-frequency driver and a four-inch low-frequency driver were used to generate white noise in a source chamber in Fig. 5. A half-inch microphone (GRAS) was used to measure the sound pressure levels at six microphone positions in each chamber.

We applied the sound waves of 400 - 5,000Hz with a sound level of about 90dB from two emitters positioned diagonally with about 100 degrees in Fig. 5. The transmission losses for the

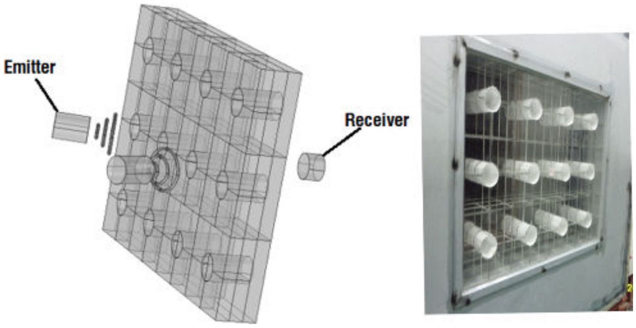

FIG. 5. Diagram and picture in the measurement of the 50mm window.

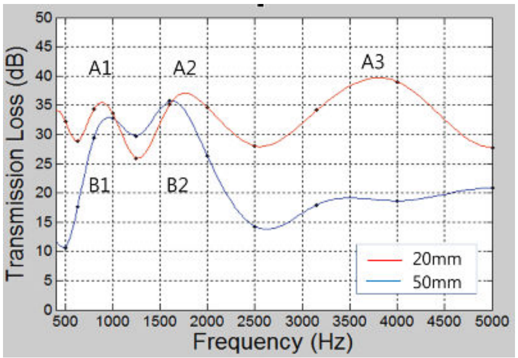

FIG. 6. Transmission loss of the air transparent soundproof windows. The x-axis is 1/3 Oct. band center frequency. The red line is for the 20mm window and the blue line is for the 50mm window.

two soundproof windows are plotted in Fig. 6 with spline fits. The sound level is reduced by about 30 - 35dB in the frequency range of 400 - 5,000Hz in the 20mm window and by about 20 - 35dB in the range of 700 - 2,200Hz in the 50mm window. Each cell creates each peak in principle. We connected three different cells, but we can see only two peaks, B1 and B2 in the 50mm window. The highest one of the 50mm window is cutoff by the diffraction condition in Eq. (1). Thus, the cutoff frequency is about 2,400Hz and it corresponds to $f_c = v/2.8D$. That is, the condition for the strong diffraction of the 50mm window is $\lambda > 2.8D$. It is an empirical value depending on the geometry of the window. It could be compared with the Fraunhofer diffraction of circular aperture. The intensity I of the diffracted wave is a function of the Bessel function J_1.[25]

$$I(x) \propto \left\{ \frac{2J_1(x)}{x} \right\}^2, \tag{5}$$

where $x = \pi D \sin\alpha/\lambda$, and α is the angle of the diffracted wave measured from the center of the aperture. Note that $I(0) = 1$ and $I(x)$ has first minima at $x = 3.83$. For the diffraction resonator, $\sin\alpha \simeq 1$. Then, the cutoff wavelength $\lambda = 2.8D$ corresponds to $x = 1.1$ and about 70% of the maximum intensity. However, this cutoff frequency depends on the geometry of the window, too.[21]

An installation of the air transparent soundproof window near a highway is shown in Fig. 7. It blocked the frequency range over 200Hz effectively and reduced the sound level about 20dB with moderate airflow. See Ref. 26 for a short movie of the performance of the window. It will be helpful for the people who are living near a street without cooling system in summer.

IV. SUMMARY

We have presented an extraordinary acoustic anti-transmission through sub-wavelength apertures. For air-transparent soundproofing, we suggested two conditions. One is strong diffraction and

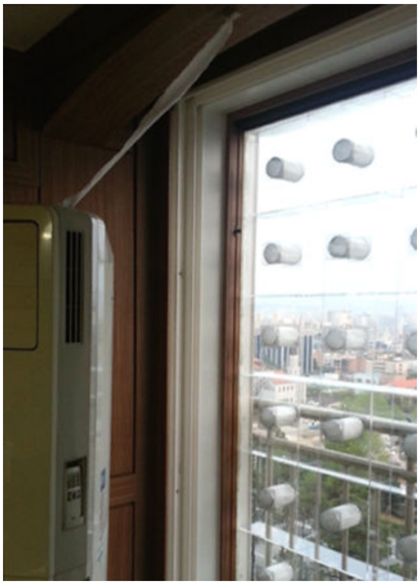

FIG. 7. An example of the air transparent soundproof window installed near a highway. The diameter of the air hole is 7cm. See Ref. 26.

the other is an effective negative bulk modulus. Applying the two conditions, we have designed a soundproof window that macroscopic ventilation is available. The window is composed of many diffraction resonators or cells connected in series and parallel positions. The diameter of the hole in the atoms should be smaller than the wavelength of the sound wave for strong diffraction; the diameters of the holes being 20mm and 50mm. We created a resonator to intercept sound from the sound waves in certain frequency ranges, which led to the separation of the medium and the sound. Afterwards, we applied sound waves of about 90dB in the range of 400 - 5,000Hz to the windows. We then observed a serious transmission loss of sound within specific frequency ranges. The loss was 20 - 35dB in the 50mm window, which is in the range of 700 - 2,200Hz.

The soundproof frequency range is tunable. The range can be adjusted by several factors, such as the volume of the resonator, the entrance area of the resonator, the size of the air hole, the property of the air filter, etc. A filter with variable impedance allows the adjustment of the soundproof frequency ranges. There is a wide range of application areas, such as soundproofing windows for houses close to noisy areas, or the soundproofing walls in residential areas. etc. It helps cooling and saving energy. These principles should work in water as well as in air and may contribute to underwater noise reduction for marine life.

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[26] See http://www.youtube.com/watch?v=VZ36PqHT9iw for the demonstration of the air transparent soundproof window.