Air transparent soundproof window

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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 incarnated on the medium by pressure, therefore, it is not surprising to believe that the medium and sound cannot be separated. One of the most interesting topics in acoustics for years is the extraordinary acoustic transmission (EAT) through subwavelength apertures in plates after a series of pioneering works in extraordinary optical transmission (EOT) \cite{1, 2}. It has been known that the extraordinary transmission of sound is similar to its optical counterpart EOT \cite{3, 4, 5}. Most of the previous works were the EAT of many holed plates or a large transmission at a specific frequency \cite{6, 7}. However, an anti-transmission that allows a medium to pass through a holed structure but blocks the sound has not been studied very much.

In recent years the research on EAT has accelerated due to the fast development of acoustic metamaterials. The separation between sound and medium has been successfully demonstrated \cite{10}. The key is the Helmholtz resonators. It makes the effective bulk modulus of the medium negative. It is not a new system, but a new interpretation of the acoustic resonance. If the medium and sound are separated, we cannot hear the sound because the sound wave cannot travel without a medium, but we can still feel the medium or air pressure because the medium can travel without the sound. With the help of a modified Helmholtz resonator, we designed a soundproof window or wall where air is allowed to flow freely within some specific frequency ranges. The air transparent window is a medium-sound separator and the reverse form of the EAT - an extraordinary acoustic anti-transmission (EAAT).

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. A common bottle-type Helmholtz resonator is not suitable for the purpose. Therefore, we designed another resonator of an artificial atom and called it a \textit{diffraction resonator} in Fig. 1. It has an air hole in the center of the body to maximize the diffraction effect. The atom is composed of one, two, or four resonators. The air hole and the resonator are separated by an air filter \cite{11} to match the acoustic impedance. Without the filtering it may create the noise of a wind instrument. Afterwards, we composed the artificial atoms in parallel and series to construct the window. It is made of transparent acrylic of a thickness of 5mm. The inner dimension of each atom is $150\text{mm} \times 150\text{mm} \times 40\text{mm}$. The diameters of the air holes are 20mm and 50mm. It is different from a perforated sheet or the acoustic pipes of low-pass filters \cite{12, 13}. The 20mm window is designed to measure background noise level of complete soundproofing while the 50mm window serves the practical purpose of noise reduction.

The diameter (D) of the air hole of the artificial atoms should be much smaller than the wavelength of the applied sound wave $\lambda$ for strong diffraction. Therefore, the upper limit of the soundproof frequency is restricted by the diffraction condition

\begin{equation}
    f < f_D,
\end{equation}

where $f_D$ is the cutoff frequency of the strong diffraction.

The second condition is the negative bulk modulus of the resonators that separate the sound from its medium. Bulk modulus $E$ is defined by $\Delta P = -E\Delta V/V$, where $V$ is the volume. The speed of an acoustic wave in fluid depends on the fluid’s compressibility and inertia. If the fluid has the bulk modulus $E$ and an equilibrium density $\rho$, then the speed of sound in it is $v = \sqrt{E/\rho}$. The resonance of accumulated waves in the resonator reacts against the applied pressure at some specific frequency ranges. The negative modulus is then realized by passing the acoustic wave through the resonators. By this procedure the amplitude of the sound wave is attenuated exponentially by imaginary velocity or imaginary wavevector. The general form of the effective bulk modulus of acoustic waves is given by the complex form similar with

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FIG. 1: Artificial atoms of diffraction resonators. Diameters of the air holes: 20\(\text{mm}\) for (a1), (a2), and (a3), and 50\(\text{mm}\) 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).

FIG. 2: A typical plot of effective modulus around resonance. The arrowed region of the frequency has a negative real part of the modulus.

The effective electric permittivity is

\[ E^{-1}_{\text{eff}} = E^{-1} \left[ 1 - \frac{F \omega_o^2}{\omega^2 - \omega_o^2 + i \Gamma \omega} \right] , \]

(2)

where \(\omega_o\) is the resonance frequency, \(\Gamma\) 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. 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

\[ f_o < f < \sqrt{1 + F f_o} , \]

(3)

where \(f_o = \omega_o/2\pi\). This is the second condition for soundproofing. 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, and will be estimated by a combined method of theory and experiment.

We plotted the two conditions of the soundproof together in Fig. 3. For the soundproof window the two conditions of Eq. (1) and Eq. (3) must both be satisfied. There is no soundproof in (c). 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.

The sample soundproof window has an array of 3\(\times\)4\(\times\)3 artificial atoms arranged in parallel and series positions like the resonators in Fig. 4. We connected three pieces of the artificial atoms in Fig. 4 in series. The first piece has one room, the second one has two rooms, and the third one has four rooms. The number of rooms is the number of the resonators. The large volume or small entrance area corresponds to the low resonant frequency. By this structure the window has three different stop-bands.

The minimum length of the air passage for the soundproof is obtained from the imaginary wave-vector. The amplitude of the plane wave attenuates as \(e^{ikx} = e^{-2\pi |n| x / \lambda} \), where \(|n|\) is the refractive index in the resonator and is close to 1. For the attenuation of the amplitude of 1/e, the length of the air passage is \(x = \lambda/2\pi\). However, it is not necessary to be too long due to the background noise level. The thickness or total pure length of the air passage of the windows is 40\(\text{mm}\) \(\times\) 3 = 120\(\text{mm}\). We can make the thickness of the window thinner if we curve the passage of the air.

The measurement of sound transmission loss using small chambers has been carried out in accordance with the test standards for large reverberation rooms: ISO 10140:2010, ASTM E 90:2004. The test facility called...
as ‘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: $W1.2m \times H1.0m$, (b) volume of Source Room: $2.808m^3$, and (c) volume of Receiving Room: $3.252m^3$. We applied the sound waves of $400 - 5,000Hz$ with a sound level of about $80dB$ from two emitters positioned diagonally with about 100 degrees in Fig. 3. The distance between the emitters and the window is $1.200mm$ and the distance between the receiver and the window is $400mm$.

The transmission losses for the two soundproof windows are plotted in Fig. 6 with spline fits. The small lowest frequency peak at around $300Hz$ may come from a periodic structure of the window. The sound level is reduced by about $30 - 35dB$ in the above frequency range with the $20mm$ window, and by about $20 - 35dB$ in the frequency range of $700 - 2,200Hz$ with the $50mm$ window. Each atom creates each peak in principle. We connected three different atoms, but we can see only two peaks, B1 and B2 at the $50mm$ window. The highest one of the $50mm$ window is cutoff by the diffraction condition in Eq. (4). It means that the cutoff frequency is about $2,400Hz$ and it corresponds to $f_D \approx v/3D$. The $20mm$ window corresponds to (a) and the $50mm$ window corresponds to (b) in Fig. 3.

The resonance frequency of the artificial atoms is obtained approximately from that of the bottle-type Helmholtz resonator $[12, 15]$.

$$f_o = \frac{v}{2\pi} \sqrt{\frac{S_H}{V_H}} \approx \frac{v}{2\pi} \sqrt{\frac{\pi r_e}{0.85V}} = \frac{v}{2\pi} \sqrt{\frac{\pi NDt}{0.85V}}. \tag{4}$$

$S_H$ and $V_H$ are the neck area and volume of the Helmholtz resonator. $S$ and $V$ are the surface area of the entrance and the volume inside of the artificial atom. Then, we have $V_H = V/N$ and $S = \pi Dt/N \equiv \pi r_e^2$, where $D$ is the diameter of the air hole, $t$ is the thickness of the atom or the length of the air passage, and $N$ is the number of rooms or number of resonators. $l_e$ is the effective length of the neck given as $l_e = l + 0.85r_e$ and $r_e$ is the effective radius of the entrance of the diffraction resonator $[15]$. It gives the effective radius as $r_e = \sqrt{D/\pi N}$. Note that $l_e = l + 0.85r_e \approx 0.85r_e$ since $l << r_e$.

TABLE I: Resonance frequencies and the corresponding geometric factors.

| Resonator | Rooms | $f_o(Hz)$ | $f_{peak}(Hz)$ | $F$ |
|-----------|-------|-----------|---------------|-----|
| A1        | 1     | 590       | 900           | 3.3 |
| A2        | 2     | 700       | 1700          | 14  |
| A3        | 4     | 830       | 3800          | 62  |
| B1        | 1     | 770       | 950           | 1.2 |
| B2        | 2     | 910       | 1600          | 5.3 |

The geometric factor $F$ is estimated from Eq. (3) if the stop-band in Fig 2 is symmetric

$$\sqrt{1 + F} = \frac{2f_{peak}}{f_o} - 1, \tag{5}$$

where $f_{peak}$ is the peak frequency and read from the Fig. 6. $f_o$ is obtained from Eq. (4). We can estimate the geometric factor $F$ in Eq. (2) of every atom in Fig. 1. We summarized the $F$ in Table 1. If we use various air filters, we may have different results. We observe that the geometric factor $F$ increases as the number of rooms increases. $F$ is roughly proportional to the square of the number of rooms.

We have presented an extraordinary acoustic anti-transmission (EAAT) through subwavelength apertures. For air transparent soundproof, we suggested two conditions. One is the strong diffraction and the other is the effective negative modulus. Through applying the two conditions, we have designed a soundproof window where air passes through freely. The window is composed of many artificial atoms or diffraction resonators connected in series and parallel. The diameter of the hole in the artificial atoms should be much less than the wavelength of the sound wave for a strong diffraction; the diameters of the holes being $20mm$ and $50mm$. We created the resonator to intercept sound from the sound waves at some frequency ranges which led to a separation of the medium and sound. Afterwards, we applied sound waves in the range of $400 - 5,000Hz$ to the two windows.
We then observed a serious transmission loss of sound within specific frequency ranges. The loss was 20 – 35dB with the 50mm window in the range of 700 – 2, 200Hz.

This air transparent window was not designed for complete soundproof but for noise reduction. The frequency range of soundproofing could 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. The thickness of the window could be very thin if we used a curved passage of air. The geometric factor of the effective bulk modulus was estimated. However, we needed to improve it by considering the properties of the air filter and the asymmetry of the stop-band.

The structure of the air transparent soundproof window or wall is so simple that any carpenter can make it. The soundproof frequency range is tunable. There is a wide range of application areas such as soundproof windows of houses close to noisy area, the soundproof walls in residential areas, etc. For example, if we are in a combined area of sounds from sea waves of low frequency and noises from machine operating at a high frequency, we can hear only the sounds from sea waves with fresh air. 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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