Low-Frequency Low-Reflection Bidirectional Sound Insulation Tunnel with Ultrathin Lossy Metasurfaces

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Abstract: We report both numerical and experimental constructions of a tunnel structure with low-frequency low-reflection bidirectional sound insulation (BSI). The designed tunnel was constructed from a pair of lossy acoustic metasurfaces (AMs), which consists of six ultrathin coiled unit cells, attached on both sides. Based on the generalized Snell’s law and phase modulations for both AMs, the tunnel with the low-frequency BSI was constructed based on sound reflections and acoustic blind areas created by the AMs. The obtained transmittances were almost the same for sound incidences from both sides and were lower than −10 dB in the range 337–356 Hz. The simulated and measured results agreed well with each other. Additionally, we show that the low-reflection characteristic of the tunnel can be obtained simultaneously by thermoviscous energy loss in coiled channels of the unit cells. Finally, an interesting application of the designed tunnel in an open-window structure with low-frequency low-reflection BSI is further simulated in detail. The proposed tunnel based on the ultrathin lossy AMs has the advantages of ultrathin thickness (about λ/35), low-frequency low-reflection BSI, and high-performance ventilation, which may have potential applications in architectural acoustics and noise control.

Keywords: acoustic metasurfaces; low-frequency sound insulation; low reflection; phase modulations; thermoviscous loss

1. Introduction

Low-frequency sound insulation has attracted more and more attention in the fields of acoustics and mechanical engineering due to its great potential in noise control, environmental protection and architectural acoustics. Generally, traditional porous and fibrous materials [1], and micro-perforated plates [2,3] have been used in sound insulation, but their thicknesses are close to the working wavelengths, resulting in a relatively large number of sound insulation structures in the low-frequency range and greatly limiting their further practical applications.

In the past few years, the rapid development of metamaterials [4–13] and metasurfaces [14–22] has provided alternative ways to design a variety of sound insulation or absorption systems that can overcome the limitations of these traditional materials. The previously demonstrated systems are mainly based on different types of unit cells, such as Helmholtz resonators designed to contain a resonant cavity with a narrow neck [23–26], membrane resonators composed of a fixed elastic film decorated with asymmetric rigid platelets [27], coherent perfect absorbers with specific complex mass density or bulk modulus [28,29], metasurface-based structures with a deep subwavelength [30–34], labyrinthine Fabry–Perot resonators with coiling channels [35,36] or split-ring resonators consisting...
of two reverse ellipse-shaped split tubes [37]. The systems designed by these types of unit cells have the advantages of subwavelength thickness and high-performance sound insulation or absorption. However, most of them have been designed to be closed, and it is therefore difficult to apply them to ventilation structures.

To overcome this, a variety of open structures with sound insulation or absorption based on different mechanisms have previously been proposed, including open sound barriers based on resonance coupling [38], coherent interference [39] and artificial Mie resonances [40], and ventilation tunnels based on Helmholtz resonances [41], destructive interference [42] and asymmetric multiple scatterings [43]. In these demonstrated structures, the sound insulation or absorption with ventilation can be shown theoretically and experimentally, but the relatively large thickness and narrow ventilation width restrict their practical applications.

Recently, a class of ultrathin structures called acoustic metasurfaces (AMs), which have sound modulation based on the generalized Snell’s law [44], have attracted more and more attention due to their wide potential application. By setting desired gradient–phase profiles, the AMs can be applied to the design of metacages [45], open tunnels [46] and windows [47,48], achieving sound insulation and ventilation simultaneously. However, the working bands of these structures are generally higher than 1000 Hz, and few of them are applied in the low-frequency region. Beyond that, the success of sound insulation is mainly determined by sound reflections created by the AMs, but in some practical scenarios, it is also necessary to create low reflection of sound through open structures. Thus, the design of low-frequency low-reflection open structures with sound insulation based on the sound modulations of AMs has become an urgent problem to be solved.

In this work, we propose a type of low-frequency ultrathin coiled unit cell that is made of epoxy resin. The parameters $e$, $w$, $d$, $l$ and $h$ represent the wall thickness, the channel width, the length of the horizontal inner plate, and the total length and thickness of the unit cell, respectively. The designed unit cell can reflect incident sound energy, leading to phase delay. Here, the parameters $l$, $w$, $e$ and $h$ are selected as 70.0 mm, 6.0 mm, 1.5 mm and 28.5 mm, respectively, and the parameter $d$ is tunable, which means it can be used to modulate the reflected phase delay of the unit cell. Throughout this work, we use the software of COMSOL Multiphysics to numerically simulate low-frequency low-reflection BSI through the tunnel; the settings of numerical models are listed in Table 1. Additionally, the thickness of the thermoviscous acoustic boundary layer is
\[d_v = \sqrt{\frac{2 \mu}{\rho \omega}}\] [25], in which the parameters \(\mu\), \(\rho\) and \(\omega\) are the coefficient of dynamic viscosity, the density of air and the angular frequency, respectively. The material parameters of epoxy resin and air in the numerical models are shown in Table 2. Figure 1b shows the reflected phase delays created by the unit cells with different values of \(d\) at 370 Hz. We can see that the reflected phase delay can cover almost the whole range of \(2\pi\) by changing \(d\), and therefore, a low-frequency reflected AM with an arbitrary phase profile can be constructed based on the proposed unit cell.

![Figure 1](image-url)

**Figure 1.** (a) Schematic of a low-frequency ultrathin unit cell with a coiling space structure. (b) Phase delays of a normally incident wave created by the unit cell as a function of parameter \(d\) at 370 Hz. Six red open circles represent the selected units, with \(d = 6.0\) mm, 9.4 mm, 11.7 mm, 13.4 mm, 14.8 mm and 16.1 mm from left to right.

**Table 1.** Settings of numerical models.

| Numerical Model                        | Setting                                      |
|----------------------------------------|----------------------------------------------|
| Region out of the unit cell            | Module of Acoustic Pressure                  |
| Region in the unit cell                | Module of Thermoviscous Acoustic-Solid       |
| Surfaces of the unit cell              | Interaction                                  |
| Interfaces between regions in and out of unit cells | Thermoviscous acoustic boundary layers       |
|                                       | Acoustic-thermoviscous acoustic coupling boundary |

**Table 2.** Material parameters of numerical models.

| Parameter                      | Epoxy Resin | Air                                            |
|--------------------------------|-------------|------------------------------------------------|
| Density (\(\rho\))            | 1180 kg/m³  | \(p_0 M / RT\)                                 |
| Longitudinal wave velocity (\(c_l\)) | 2720 m/s   | \(\sqrt{\gamma RT / M}\)                      |
| Transversal wave velocity (\(c_t\)) | 1460 m/s   | /                                              |
| Molar mass (\(M\))            | /           | 28.97 \times 10^{-3} kg/mol                    |
| Ratio of the molar heat capacities (\(\gamma\)) | /          | 1.4                                            |
| Molar gas constant (\(K\))    | /           | 8.31 J/(mol/K)                                 |
| Air pressure (\(p_0\))        | /           | 101.325 kPa                                    |
| Air temperature (\(T\))       | /           | 293 K                                          |
| Coefficient of dynamic viscosity (\(\mu\)) | /        | 1.56 \times 10^{-5} Pa·s                      |

Figure 2a shows the designed AM composed of six unit cells, in which the values of \(d\) are selected as 16.1 mm, 14.8 mm, 13.4 mm, 11.7 mm, 9.4 mm, and 6.0 mm for the unit cells from left to right. The phase gradient \(d\varphi / dx = -k\), where \(k = 2\pi / \lambda\), is the wave number in air, and \(\lambda\) is the wavelength. The theoretical continuous and discrete phase delays of the AM are shown in Figure 2b, and the photograph of the AM fabricated with epoxy resin.
based on a 3D printing technology is exhibited in the upper inset. The AM can modulate the phase delay of reflected waves based on its phase gradient. Based on the generalized Snell’s law \([44]\), the relationship between the incident angle \(\theta_i\) and the reflected angle \(\theta_r\) created by the AM is expressed as

\[
\sin \theta_r = \sin \theta_i + \frac{1}{k} \frac{d\varphi}{dx},
\]

in which \(\theta_i\) and \(\theta_r\) are defined as those between the incident and reflected directions and the normal line (black dashed line), and the signs + and − of both angles represent the right and left propagation directions, respectively. Here, by substituting the phase gradient \(d\varphi/dx = -k\) into Equation (1), we can obtain

\[
\sin \theta_r = \sin \theta_i - 1. \tag{2}
\]

![Figure 2](image)

**Figure 2.** (a) Schematic of designed AM composed of 6 unit cells. (b) Theoretical continuous (blue solid line) and discrete (red open circles) phase delays of the AM. Schematic of theoretical propagation paths of the reflected waves (blue solid arrows) created by the AM for the incident waves (red solid arrows) with the angles (c) \(\theta_i = 90°\), (d) \(30° < \theta_i < 90°\), (e) \(\theta_i = 30°\), (f) \(0° < \theta_i < 30°\), (g) \(\theta_i = 0°\) and (h) \(-90° < \theta_i < 0°\).

Figure 2c–h show the theoretical propagation paths of reflected waves through the AM with different incident angles. Here, based on Equation (2), we can theoretically calculate the reflected angles \(\theta_r = 0°\), \(-30°\) and \(-90°\) for the incident angles \(\theta_i = 90°\), \(30°\) and \(0°\), which are shown in Figure 2c,e,g, respectively. Beyond that, when the incident angle decreases from \(90°\) to \(30°\) (Figure 2d) and from \(30°\) to \(0°\) (Figure 2f), the corresponding reflected angles change from \(0°\) to \(-30°\) and from \(-30°\) to \(-90°\), respectively. Here, note that the incident waves with the angle \(0° \leq \theta_i \leq 90°\) cannot reach the right side of the AM (yellow region), which is defined as an acoustic blind area (ABA). As shown in Figure 2h, when the incident angle is inside the ABA (\(-90° \leq \theta_i < 0°\)), we obtain \(\sin \theta_r < -1\) based on Equation (2); therefore, the incident sound energy cannot be reflected by the AM but is transformed as the form of surface evanescent wave \([44]\).

3. Design and Performance of Low-Frequency Low-Reflection BSI Tunnels

Next, we designed a low-frequency low-reflection BSI tunnel, which consisted of a pair of ultrathin AMs attached symmetrically on both sides. The schematic diagram of the
The proposed tunnel is shown in Figure 3a, in which a cylindrical sound source was separately placed at the point O or O’ in the following studies. The corresponding settings of the numerical models are shown in Table 1. Figure 3b,c show the simulated transmittance and reflectance spectra through the tunnel, respectively. We can see that the transmittance spectra were almost the same for both cases, and the transmittances were below −10 dB in the range 337–356 Hz (black shaded region), with a minimum value of −27 dB at 343 Hz, showing a typical characteristic of low-frequency BSI. Beyond that, the thickness h of the AM was 28.5 mm, which is equal to λ/35 at the valley of spectra, exhibiting an ultrathin characteristic of the AM. However, it is worth noting that the incident sound energy was not reflected totally for both cases (shown in Figure 3c), and the reflectance spectra were different in the working band, in which the reflectances excited by the cylindrical sound source at O’ were obviously lower than those at O, a result that may have arisen from different mechanisms of sound modulations on both sides.

![Figure 3. (a) Schematic of a tunnel structure with low-frequency low-reflection BSI. A cylindrical sound source is separately placed at the point O or O’. The tunnel width H is 343 mm. The distance between the sound source and adjacent tunnel entrance is 100 mm. We simulated (b) transmittance and (c) reflectance spectra through the tunnel by separately placing a cylindrical sound source at the points O and O’. Black shaded regions show the sound transmittances below −10 dB.](image)

4. Mechanisms of Low-Frequency Low-Reflection BSI

To provide insight into the mechanisms of low-frequency BSI, we present the schematic diagrams of propagation paths in the tunnel for the left and right incidences of sound based on wave modulations of both AMs. As shown in Figure 4a, for the incident wave I1 from the left side with the angle \( \theta_1 = 90^\circ \), the sound energy was reflected by the upper AM with \( \theta_r = 0^\circ \) and then was reflected back by the bottom AM with \( \theta_r = -90^\circ \). Beyond that, for the other incident waves with the arbitrary angle in the range \( 0^\circ < \theta_i < 90^\circ \) (I2 in Figure 4b), the incident wave was reflected by the upper AM with the angle \( \theta_r < 0^\circ \), and therefore, the sound energy was reflected to the bottom AM, which was transformed into the surface evanescent wave owing to the ABA. Figure 4c,d show the propagation paths of the incident waves I3 and I4, respectively, from the right side with the arbitrary angle in the range \( -90^\circ \leq \theta_i < 0^\circ \). We can see that I3 and I4 could be directly transformed into the surface evanescent wave by the AMs on both sides of the tunnels, owing to the ABA. Therefore, based on the sound reflections and the ABA created by the gradient phase of the AMs, the incident sound energy on both sides could not transmit through the tunnel.

In addition to the low-frequency BSI, we also simulated the low-reflection characteristic of the tunnel. Figure 5a shows the simulated total pressure distributions and the corresponding reflected pressure distributions through the tunnel by separately placing a cylindrical sound source at O and O’ at 343 Hz. We can see that the incident sound energy almost could not transmit through the tunnel in both cases, showing the characteristic of low-frequency BSI. However, as shown in the middle two insets, there still existed a certain amount of reflected sound energy for the sound incidences from both sides. It is obvious that the sound reflection from the sound source at O’ was much weaker than that at O.
showing the typical characteristics of low-reflection sound for the left and right incidences, especially for the right incidence, which agrees well with that in Figure 3c.

Figure 4. Schematic of acoustic propagation paths through the tunnel for the incident waves (a) I1, (b) I2, (c) I3 and (d) I4.

Figure 5. (a) We simulated total pressure distributions and corresponding reflected pressure distributions through the low-frequency BSI tunnel by separately placing a cylindrical sound source at O and O’ at 343 Hz. We also simulated thermoviscous loss density distributions in the unit cells by separately placing a cylindrical sound source at the points (b) O and (c) O’ at 343 Hz.

Next, we also simulated the distributions of thermoviscous loss density in the unit cells of both AMs for the left and right incidences at 343 Hz, which are shown in Figure 5b,c, respectively. For the left incidence (Figure 5b), the thermoviscous energy loss was mainly distributed in the coiled channels of the left three unit cells, owing to the sound reflections and the existence of the ABA (Figure 4a,b). However, for the right incidence (Figure 5c), the thermoviscous energy loss was almost distributed in the coiled channels of all unit cells. This is because the sound source energy on the right side was transformed into the surface evanescent wave, propagating on the surfaces of both AMs (Figure 4c,d). Thus, the total thermoviscous energy loss in the unit cells of both AMs for the left incidence was obviously weaker than that for the right incidence, which was consistent with the reflected sound energy on both sides of tunnel (Figure 5a). Based on the above theoretical analysis, we can conclude that the low-frequency low-reflection BSI of the tunnel arose from the sound reflections and the ABA created by the AMs and the thermoviscous energy loss in the coiled channels of the unit cells.

5. Experimental Verification

To experimentally demonstrate the performance of the designed tunnel, we experimentally measured the transmittance spectra through the sample for the left and right
incidences in a straight waveguide with the size of $2 \times 0.4 \times 0.06 \text{ m}^3$. The experimental set-up is shown in Figure 6a. The sample, made of epoxy resin by 3D printing technology, was placed in the middle region of the waveguide, which was constructed from acrylic plates to satisfy the sound-hard boundary condition. The parameters of the sample were the same as those in Figure 3a. A loudspeaker, driven by a power amplifier, was placed at the left entrance to generate incident sound signals, and two 0.25 inch microphones marked as Microphones 1 and 2 were separately placed into the waveguide at Holes 1 and 2 and the Holes 3 and 4 to detect sound signals. The measured data was recorded by the controller module, and was analyzed by the software PULSE Labshop. The types of instruments used in the experimental measurement are listed in Table 3.

Figure 6. (a) Experimental set-up. Sample photograph was placed in the middle region of the waveguide. We measured and simulated transmittance spectra through the sample in a waveguide for the (b) left and (c) right incidences of plane sound waves.

Table 3. Types of instruments.

| Instrument           | Type                   |
|----------------------|------------------------|
| Power amplifier      | PA-50                  |
| Controller model     | Bruel & Kjaer 3160-A-022 |
| Microphone           | Bruel & Kjaer type-4954 |

Figure 6b,c show the measured transmittance spectra (blue open circles) through the sample for the left and right incidences of plane sound waves, respectively, in which the simulated results with the same conditions are also displayed for comparison (blue solid lines). We can see that the performances of low-frequency BSI were almost the same for both cases, and the minimum value of transmittance reached about $-31 \text{ dB}$ at $343 \text{ Hz}$. The measured spectra agreed well with their corresponding simulations. Therefore, the low-frequency BSI of the tunnel is experimentally demonstrated.
6. Application of Tunnel in Open Window with Low-Frequency Low-Reflection BSI

Finally, to further explore the practical application of the designed tunnel, we also designed an open-window structure with low-frequency low-reflection BSI, which consisted of seven tunnels (shown in Figure 7a). The structure and all parameters of the AMs on both sides of each tunnel were the same as those in Figure 3a. Figure 7b shows the simulated transmittance spectra through the open window, in which a cylindrical sound source was separately placed at the points O and O′, and the corresponding settings of the models are shown in the Table 1. We can see that the performances of low-frequency BSI created by the open window were almost the same for the sound incidence from both sides. The transmittances were lower than −10 dB in the range 341–360 Hz (black shaded region), and the minimum value reached −30 dB at 348 Hz. Figure 7c,d show the simulated total pressure distributions through the open window for both cases at 348 Hz. The simulated results obviously show that, in both cases, the incident cylindrical sound waves could not transmit through the designed open window, but the other media (such as air, heat and light) could achieve free transport on both sides, showing a perfect effect of low-frequency BSI.

![Figure 7](image)

**Figure 7.** (a) Schematic of an open-window structure with low-frequency low-reflection BSI, in which a cylindrical sound source was separately placed at the point O or O’. (b) We simulated transmittance spectra through the open window by separately placing a cylindrical sound source at the point O and O’. We also simulated pressure distributions through the open window by separately placing a cylindrical sound source at the points (c) O and (d) O’ at 348 Hz.

7. Conclusions

We demonstrated a type of low-frequency low-reflection BSI tunnel, which was constructed by a pair of ultrathin lossy AMs (about λ/35) with the phase gradient \( d\varphi/dx = -k \) attached symmetrically on both sides of a straight tunnel. Based on the generalized Snell’s law and the phase modulations by both AMs, we designed a tunnel with a low-frequency BSI, in which the transmittances were lower than −10 dB in the range 337–356 Hz, and the minimum value reached about −27 dB at 343 Hz. Such a phenomenon can be explained by the sound reflections and the ABA created by the AMs for the left and right incidences of sound. In addition to the characteristics of low-frequency BSI, the low reflection of sound through the tunnel was simultaneously achieved by the thermoviscous energy loss in the coiled channels of the unit cells. The measured results agreed well with the simulated ones.
Finally, the potential application of the tunnel in the design of an open-window structure with low-frequency low-reflection BSI was further simulated in detail.

The proposed open tunnel and window structures showed high performance characteristic of low-frequency low-reflection BSI, which has potential applications in designing sound insulation rooms. The ultrathin structure of AMs and the highly efficient ventilation of open structures provide high-performance heat dissipation. Beyond that, it can also be applied to design ventilation ducts and corridors of BSI. Future work may focus on performance modulations of open sound insulation structures.

**Author Contributions:** Conceptualization, Y.-J.G. and H.-X.S.; methodology, Y.-J.G., Y.-W.X. and Y.G.; validation, Y.-J.G., Y.-W.X. and Y.G.; formal analysis, Y.-J.G. and H.-X.S.; writing—original draft preparation, Y.-J.G.; writing—review and editing, H.-X.S.; supervision, H.-X.S., S.-Q.Y. and X.-J.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the National Key Research and Development Program of China (Grant No. 2020YFC1512403), the National Natural Science Foundation of China (Grant Nos. 12174159 and 11834008) and the Practice Innovation Training Program Projects of Jiangsu Province (Grant No. 202110299082Z).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data are contained within the article. Further inquiries can be directed to the corresponding authors.

**Conflicts of Interest:** The authors declare no conflict of interest.

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