Light-weight large-scale tunable metamaterial panel for low-frequency sound insulation

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To overcome the traditional problem of blocking low-frequency noise, this letter proposes a design of large-scale metamaterial panel with periodic tunable resonant cell arrays. Numerical calculations show that the tunable metamaterial panels exhibit multiple local resonance mechanisms, which result in sound transmission loss (STL) improvements over traditional mass law in low-frequency regions. The effective dynamic mass of traditional sound insulation material usually only increases. Blocking low-frequency sound is always a conventional challenge. New physical mechanisms are needed to overcome the problem of low-frequency sound insulation.

Over the past decade, acoustic metamaterials, which are generally considered to be artificial composites with carefully designed micro resonant units, have attracted increasing interest.1–6 Owing to their unusual properties that natural materials do not possess, acoustic metamaterials provide innovative ways to manipulate the propagation of acoustic wave and they are promising for many applications, such as sound insulation,10–12 vibration attenuation13–17 and so on.

Ever since Liu et al. proposed an acoustic metamaterial with periodic coated spheres and experimentally demonstrated the exceptional low-frequency sound attenuation performance,14 a new route to the low frequency noise suppression has been opened. To blocking low-frequency noise with thin and light weight structures, Yang et al. developed a membrane-type acoustic metamaterial using elastic membrane fixed by a rigid frame with a small weight attached to the center.15,16 They demonstrated it can realize much higher sound transmission loss (STL) than that given by the mass law in the low-frequency regime. Since then, research interest in membrane-type acoustic metamaterials has grown rapidly and many interesting findings has been yielded.20–24 Earlier studies on membrane-type acoustic metamaterials are always focused on small-scale structures including only one or several unit-cells with fixed boundary conditions.19,21,22 More recently, large-scale membrane-type acoustic metamaterial panels have received attention according to the requirement of using large-size partitions for practical sound insulation applications.25–27 Another class of attractive designs are plate-type acoustic metamaterials made by periodic arrays of local resonators attached to a host flexural plate. The studies show that the STL of infinite plate-type acoustic metamaterials can also break through the mass law at low frequencies.28–32 It has also been demonstrated that by appropriately tuning the local resonators, a plate-type acoustic metamaterial can further overcome the conventional coincidence effects, leading to a significant increase of STL in the coincidence region of the host plate.28 Since the governing wave equations of a tensioned membrane and a flexural plate are basically different, there are essential differences between membrane-type and plate-type metamaterials.33 More comprehensive discussions of differences between membrane-type and plate-type metamaterials are reported in a review paper.4

If weight restriction is considered in design, acoustic metamaterial is usually only suitable for narrowband acoustic insulation improvements. However, in practical implementations, due to uncertain factors such as manufacturing errors and changing working conditions, the operating frequency band of a realized metamaterial may deviate from the target frequency of noise control. Therefore, the acoustic metamaterials with tunable performance are of great practical value. Recently, to achieving tunable sound insulation performance, extensive efforts are exerted to develop acoustic metamaterials with smart structures and active components. For example, many interesting findings have been yielded on active membrane-type acoustic metamaterial unit cell.5,35,36 More recently, Zhang et al. proposed a single tunable acoustic metamaterial cell with fixed boundary conditions. Which consists of a foil bonded with piezoelectric resonators. They demonstrated that a STL peak can be obtained due to the resonant behavior caused by the piezoelectric resonators.37 However, for practical engineering applications, large-scale acoustic metamaterial panels with active unit cell arrays may be preferred. In particular, it is of great significance to experimentally validate the sound insulation performance of large-scale active metamaterial panels. To the authors’ knowledge, there is currently no report on the experimental study of large-scale active metamaterial panels.
In this study, we design a two-dimension large-scale acoustic metamaterial panel with periodic tunable resonant cell arrays, which is ultra-light. Numerical results show that the metamaterial panel exhibit multiple local resonance mechanisms, which result in multiple STL peaks and STL improvements over traditional mass law in low-frequency regions. Large-scale tunable metamaterial panel samples with 36 (6 × 6) unit cells are fabricated and experimental measurements of sound insulation performance are conducted to validate the theoretical predictions.

The proposed acoustic metamaterial panel [as shown in Figs. 1(a) and 1(b)] is formed by the sub-wavelength arrays of tunable unit cell in the x-y plane. Each tunable unit cell consists of an ultra-thin foil supported by square grid frame and pasted with tunable piezoelectric resonators, as shown in Figs. 1(c) and 1(d). The piezoelectric resonator is made of piezoelectric patch and the resistance-inductance series shunt circuit. As an illustration, the geometrical parameters of unit cell are chosen as \( l_x = w_x = 65 \text{ mm}; h_y = 10 \text{ mm}; l_y = w_y = 60 \text{ mm}; h_z = 0.1 \text{ mm}; l_z = w_z = 40 \text{ mm}, \). The foil is made of aluminium with Young’s modulus 70 GPa, Poisson’s ratio 0.35, and mass density 2730 kg m\(^{-3}\). The piezoelectric patch is PZT-5H with dielectric constant \( \varepsilon_{33}^T = 3.01 \times 10^{-9} \text{ F m}^{-1} \). The grid is Plexiglas with Young’s modulus 4.5 GPa, Poisson’s ratio 0.39, and mass density 1062 kg m\(^{-3}\). By using the material parameters and structural parameters mentioned above, the areal mass density of the proposed metamaterial panel can be calculated, which is only about 2.98 kg m\(^{-2}\).

To predict the sound insulation behavior of the acoustic metamaterial panels, a dynamically coupled finite element (FE) model for one unit cell and the related air media has been developed by employing the well-known FE software: COMSOL Multiphysics 5.0, as shown in Fig. 1(e). Periodic boundary conditions are used to the lateral faces of the unit cell and air domains according to the Bloch theorem for periodic systems. The normal incident plane wave is produced by a back-ground pressure field. Previous studies have shown that the normal incidence case is representative to characterize low frequency sound insulation performance of metamaterial panels.\(^{25,28}\) Perfectly matched layer absorbing boundary conditions are applied at the terminal of the air media. In the simulation, standard values are used for the parameters of air media, i.e., the mass density and sound velocity are \( \rho_0 = 1.21 \text{ kg m}^{-3} \) and \( c_0 = 340 \text{ m s}^{-1} \), respectively.

The simulated STL spectra is shown in Fig. 2(a). In order to fully investigate the sound insulation properties of the acoustic metamaterial panel, the shunted case (i.e., all of the resistance-inductance shunting circuits are closed and piezoelectric resonators work) and unshunted case (i.e., all of the resistance-inductance shunting circuits are opened and piezoelectric resonators no longer work) are both examined. Further more, by comparison, the STL given by the mass law is also presented.

Firstly, we analyse the STL spectrum of shunted metamaterial panel, as shown in Fig. 2(a) with solid line. As an illustrative example, the inductance and resistance of the shunting circuits are chosen as \( L = 0.18 \text{ H} \) and \( R = 2 \Omega \), respectively. It can be seen that the predicted STL of shunted metamaterial panel rises from 50 Hz, then three peaks \( f_{d1} = 305 \text{ Hz}, f_{d2} = 817 \text{ Hz} \) and \( f_{d3} = 1445 \text{ Hz} \) and two dips \( f_{d4} = 348 \text{ Hz} \) and \( f_{d5} = 855 \text{ Hz} \) alternately appear as the frequency increasing. The sound insulation performance of the shunted acoustic metamaterial breaks though the mass law in three regions of the frequency bandwidth 50–330 Hz, 475–837 Hz and 970–1500 Hz. It indicates that the proposed metamaterial panel can be used for low-frequency sound insulation.

Figure 2(a) also shows the STL spectrum of the unshunted acoustic metamaterial panel by dotted line. It is interesting to note that STL improvements over mass law are still observed in low-frequency regions (50–354 Hz and 570–1465 Hz). Comparing the STL spectrum of unshunted metamaterial panel with that of shunted metamaterial panel, the main difference is that the peak around \( f_{d2} \) and the dip around \( f_{d3} \) disappear. In contrast, the peaks around \( f_{d1} \) and \( f_{d3} \) and the dip around \( f_{d4} \) still exist on the STL spectrum of unshunted metamaterial panel, but slightly shift in frequency location. This implies that the proposed metamaterial panel exhibits multiple local resonance mechanisms. The formation of the peak around \( f_{d2} \) is due to the locally resonant behavior.

![Fig. 1](image-url) (Color online) Sketch of the tunable acoustic metamaterial panel: (a) Isometric view and (b) side view. Sketch of the unit cell: (c) Isometric view and (d) side view. (e) Finite element model of the tunable acoustic metamaterial panel.
produced by the active piezoelectric resonators, which is similar to the STL peak observed in previous work by Zhang et al.\textsuperscript{37} While, the peaks around $f_{p1}$ and $f_{p3}$ are caused by passive local resonances, in which the piezoelectric patches act like a mass. The mechanisms of the passive local resonances have been revealed by Yang et al.\textsuperscript{18,19} and Langfeldt et al.\textsuperscript{24–26} The proposed metamaterial panel is designed by combining multiple known STL peak formation mechanisms, thus it exhibits prominent sound insulation performance over multiple frequency bands.

To gain further insight to the local resonance behaviors, the displacement vector fields of one unit cell in the large-scale shunted metamaterial panel at frequencies $f_{p1} = 305\, \text{Hz}$, $f_{p2} = 817\, \text{Hz}$ and $f_{p3} = 1445\, \text{Hz}$ are illustrated in Figs. 2(b)–2(d), respectively. At the frequency $f_{p1} = 305\, \text{Hz}$, the displacement of grid is out-of-phase with that of PZT patches. At the frequency $f_{p2} = 817\, \text{Hz}$, the vibration of the foil surrounding PZT patch goes out-of-phase with that of the rest part. While, at the frequency $f_{p3} = 1445\, \text{Hz}$, the grid does not seem to vibrate, but the displacement of the central part of the metamaterial is out-of-phase with that of the part in the corner.

In Fig. 2(e), we examined the normalized effective dynamic areal mass density $\rho_{\text{eff}} / \rho_a$ of the metamaterial panel. Where $\rho_{\text{eff}} / \rho_a$ is the averaged pressure on the acoustic metamaterial panel. $\rho_a = 2.98\, \text{kg m}^{-2}$ is the static areal mass density. It can be seen the effective dynamic mass density $\rho_{\text{eff}}$ varies with the frequency. By comparing Figs. 2(a) and 2(e), it can be found that the effective dynamic areal mass density $\rho_{\text{eff}}$ tends to infinitely large at the peak frequencies ($f_{p1} = 305\, \text{Hz}$, $f_{p2} = 817\, \text{Hz}$ and $f_{p3} = 1445\, \text{Hz}$), and becomes zero at the dip frequencies ($f_{d1} = 348\, \text{Hz}$ and $f_{d2} = 855\, \text{Hz}$). Previous literatures also indicated the excellent STL of the acoustic metamaterial is closely related to the effective dynamic areal mass density $\rho_{\text{eff}}$.\textsuperscript{19,25,37} In fact, the relationship between them can be expressed in the explicit formulations $\text{STL} = 10\log_{10} \left[ \left( \frac{\omega \rho_{\text{eff}}}{2 \rho_a c_0} \right)^2 \right]$.\textsuperscript{37}

To understand the infinitely effective dynamic mass density $\rho_{\text{eff}}$ at the peak frequencies, we examined the averaged normal acceleration $\ddot{\bar{a}}$. The curve of acceleration amplitude $|\ddot{\bar{a}}|$ is shown in Fig. 2(f). It is observed that at the peak frequencies ($f_{p1} = 305\, \text{Hz}$, $f_{p2} = 817\, \text{Hz}$ and $f_{p3} = 1445\, \text{Hz}$), local resonance behaviors result in the infinitely effective dynamic mass density $\rho_{\text{eff}}$ should tend to infinitely large.

The main advantage of active acoustic metamaterials is their tunable properties, which is more adaptable in practical applications. The sound insulation properties of the proposed acoustic metamaterial panel can be easily tuned by piezoelectric resonators. In Fig. 2(g), the dependence of STL on frequency and inductance parameter ($L$) is given. Furthermore, in Fig. 2(h), the regularities of peak frequencies and dip frequencies are also presented for a clearer illustration. An important note about Figs. 2(g) and 2(h) is that the vertical axis representing inductance value is reversed for convenient, which indicates that the inductance value is decreasing from bottom to top.

It can be seen in Figs. 2(g) and 2(h), the frequencies of first STL peak ($f_{p1}$) and the first STL dip ($f_{d1}$) increase as the inductance $L$ decreasing from 10 H, then the rate of increase gradually slowed down as the inductance $L$ tuned close to 1 H, and they ultimately tend to 306 Hz and 352 Hz. Whereas, the second STL peak frequency $f_{p2}$ and the second dip frequency $f_{d2}$ change slowly as the inductance $L$ tuned to be very large (e.g., $L \gg 1$ H) or very small (e.g., $L \ll 0.1$ H),...
but they change rapidly as the inductance changing between 1 H and 0.1 H. The third STL peak frequency \( f_{p3} \) seems almost unchanged (1380 Hz) when the inductance \( L \) is smaller than 1 H, while it moves to a higher frequency when the inductance \( L \) is tuned close to 0.1 H. In Fig. 2(h), the evolution of the resonant frequency \( f_0 \) of the piezoelectric resonators is also depicted. As can be seen, the second STL peak is dominated by the piezoelectric resonators only when the inductance is changed within the range 0.1 H < \( L < \) 1 H.

To validate the theoretical results, tunable acoustic metamaterial panel samples are fabricated and sound insulation experiments are conducted. The photo and sketch of the experimental setup are illustrated in Figs. 3(a) and 3(b). The acoustic metamaterial panel is 0.5 \( \times \) 0.5 m\(^2\) with 36 (6 \( \times \) 6) unit cells and it is mounted onto the opening of an anechoic box. In the experiment, pseudo random signals are generated by the B&K Pulse measurement system. The signals are then amplified by B&K 2732 power amplifier and applied to sound source. The averaged sound pressures level at the incident (\( L_{inc} \)) and transmitted side (\( L_{tr} \)) can be measured by scanning with the sound level meters \( M_1 \) and \( M_2 \), respectively. Thus, the measured STL spectra can be obtained by the equation STL = \( L_{inc} - L_{tr} \). Before evaluating the sound insulation property of the samples, the STL spectrum without any sample is measured. Then, the STL spectra with samples are corrected by subtracting the STL spectrum without sample.

Figure 3(c) depicts the experimentally measured STL spectra with samples. The solid line represents the measured result of the shunted metamaterial panel. In the shunting circuit, the inductance tuned to \( L = 0.18 \) H, and the resistance of resistor is chosen as \( R = 2 \) Ω. The inductor is realized by using a synthetic circuit, namely Antoniou’s circuit. The black dotted line describes the measured STL spectrum of the unshunted metamaterial panel. The dashed line shows the measured STL spectrum of aluminum plate with same areal mass density. In Fig. 3(c), it is clearly demonstrated whether the acoustic metamaterials panel is shunted or unshunted, its STL performance is better than that of aluminum plate in low-frequency regions. Compared with the STL spectrum of the unshunted metamaterial panel, it can be noted that the sound insulation property of the shunted metamaterial panel (red solid line) is significantly improved in frequency range 640–837 Hz, which agrees with the STL peak around \( f_{p2} = 817 \) Hz theoretically predicted in Fig. 2(a). It can be also seen that the theoretically predicted third STL peak is well verified by the experimental results. However, the first STL peak cannot be clearly identified from the measurements. This is due to the fact that in the low frequency range, the STL can be significantly affected by the natural vibrational modes of the finite metamaterial panel as well as the backing cavity, which are relevant to the stiffness and boundary conditions of the panel, as well as the imperfect absorption of the anechoic box. Nevertheless, the effects of the natural modes are not included in the present theoretical model, where an infinite metamaterial panel is simulated by use of periodic boundary conditions and perfect absorption conditions. As a preliminary assessment, the lowest natural frequency of the experimental sample is calculated to be 212 Hz. Therefore, at frequencies around and lower than 212 Hz, the STL of the finite experiment sample may not be well predicted by the infinite structure model. More exact FE
modelling of large-scale finite-sized metamaterial panels with proper boundary conditions is deferred in our future work.

To experimentally demonstrate the tunability of sound insulation property, Fig. 3(d) shows the experimentally measured STL spectrum of the shunted metamaterial panel with \( L = 1 \) H. For comparison, the STL spectrum of the unshunted metamaterial panel is still presented as a baseline reference. It is seen that the STL improved frequency range is tuned to 243–328 Hz. In addition, it can be found that the experimental results validate the simulation results, which are also shown in the insets.

In Figs. 3(c) and 3(d), the experimentally measured STL peaks (and dips) are not so strong as the theoretically predicted STL peaks (and dips). The reasons for this mismatch may include (but are not limited to): (i) incidence angle-dependency of the performance; (ii) stiffness and boundary conditions of the finite samples; (iii) damping in the samples; (iv) inconsistency of the unit cells.

In summary, we have designed a light-weight large-scale metamaterial panel with sub-wavelength tunable resonant cell arrays. The tunable resonant cell is composed of an ultra-thin foil supported by square grid frames and pasted with active piezoelectric resonators. We theoretically demonstrated that the STL improvement on traditional mass law is achieved in low-frequency regions. Furthermore, the study found that the acoustic metamaterial panels exhibits multiple local resonance mechanisms, which result in three STL peaks in low-frequency regions. It is showed that the effective dynamic mass density tends to infinity at the frequency of STL peaks and drops to zero at the frequency of STL dips. The tunability of sound insulation performance with changing inductance parameter is also analysed. Finally, large-scale tunable metamaterial panel samples with 36 (6 × 6) unit cells are fabricated and measured. The experimental results prove the validity of the theoretical predictions.

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