Ultra-open Manually Tunable Ventilated Metamaterial Absorbers for Environment with Free Air Flows

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Abstract

For most acoustic metamaterials, once they have been fabricated, their operating frequencies and functions cannot be adjusted, which is an intrinsic barrier for development of realistic applications. The study to overcome this limit has become an urgent issue at the heart of acoustic metamaterial engineering. Although with the advance of metamaterials in the past two decades, a series of methods such as electric or magnetic control have been proposed, most of them can only work in the condition of no fluid passage. Some metamaterials with large transmission losses have been proposed, but the sounds are essentially reflected rather than absorbed. Here, to overcome this intrinsic difficulty, we propose a ventilated sound absorber that can be manually tuned in a large range after being manufactured. During the tuning which is
achieved through an intricately designed slider, high-performance absorption and ventilation are both ensured. The tunable ventilated sound absorber is demonstrated experimentally and the effective model of coupled lossy oscillators can be employed to understand its mechanism. The manually tunable ventilated metamaterial has the potential application values in various complicated pipe systems that require frequency adjustment and it also establishes the foundation for future development of active tunable ventilated acoustic metamaterials.

**Introduction**

In the past two decades, acoustic metamaterials have developed rapidly in various fields such as acoustic cloaking\(^1\)\(^2\), subwavelength imaging\(^3\)\(^-\)\(^5\), topological acoustics\(^6\)\(^-\)\(^9\), and sound insulation and absorption\(^10\)\(^11\), providing unprecedented ways to control sound waves, which have fundamental theoretical and application values\(^12\)\(^-\)\(^15\). For example, the rapid development of sound-absorbing metamaterials has solved the critical issue of the low dissipation of traditional sound-absorbing structures under low-frequency sound waves (< 500 Hz) which resulting in inefficient absorption of sound energy\(^13\)\(^14\)\(^16\)\(^-\)\(^19\). However, these acoustic metamaterials cannot work with free fluid such as air. The acoustic metamaterials that can work in free fluid have been proposed but cannot solve the problem of absorption of low frequency sound\(^20\)\(^-\)\(^27\). Furthermore, the majority of acoustic metamaterials that have been proposed and demonstrated in the past two decades are passive with fixed geometries. Once they have been fabricated, their operating frequencies and functions cannot be tuned, which is a stringent barrier for development of realistic applications. To overcome this restriction, tunable acoustic metamaterials have been proposed and investigated in recent years. Some tunability mechanisms have been presented, mainly employing the mechanical deformations, piezoelectric, and/or magnetic effects\(^28\)\(^-\)\(^31\). However, they all require rigid backings to terminate sound transmissions, which also forbid the transmission of fluids, such as air and water. Further, their complex and intricate mechanical, electronic, and/or magnetic structures are not convenient and
robust for everyday applications, and a simple adjustment method are much desired.

In this Letter, a manually tunable ventilated metamaterial absorber (MTVMA) are proposed and experimentally demonstrated. As mentioned, previous tunable acoustic metamaterial absorbers only work in the condition of no transmissions and generally employ the electromechanical or magnetomechanical effect which requires external circuits and structures to be effectively adjusted. In contrast, the MTVMA can work in an open and ventilated environment, and can be simply manually adjusted to suit for different working frequencies. Therefore, it can simultaneously achieve high-performance acoustic absorption (>85%) and ventilation (>50% open area) within a large range of tunable working frequencies. In brief, the MTVMA is comprised of carefully designed weakly coupled split-tube resonators with spatial inversion symmetry \textsuperscript{21,32-35}, and its absorption is demonstrated through numerical calculations and experimental measurement. It provides a direct route for simultaneously achieving tunable working frequency through adjustable geometry and high-efficiency absorption with ventilation at low frequencies. The practical applications can be found in various acoustic engineering scenarios where open environment must be accommodated while in dealing with a variety of noise sources.

**Results**

The MTVMA unit is comprised of two Helmholtz resonators (HRs) with the spatial inversion symmetry, and the units are assembled as schematically illustrated in Fig. 1(a). A large hollows in the upper part of the frame permit the background fluid (here, the air) freely passing through the structure. In this work, it is assumed that the all MTVMAs are immersed in air. The absorber demonstrated here is consisted four MTVMA units arranged in a rectangular lattice, and the lattice constants of MTVMA are L and L/4 along the x and y directions. The frequency of MTVMA can be changed by moving the slider to realize tunable frequency. The sound wave should be absorbed near perfectly which incident on the MTVMA units. The way to tunable the frequency by moving slider is illustrate in Fig. 1(b) and the details section view on the xy-plane
of a single MTVMA unit are depicted in Fig. 1(c). The cover is removed to demonstrate the details of the MTVMA unit (note that the structure is rotated by 90° for better visualization). Each MTVMA is composed of two split-tube resonator which is weakly coupled through the slit between the two cavities. The MTVMA are fabricated by using a three dimensional (3D) printer with the accuracy is 0.1 mm. The printing material is made of photosensitive resin composite, which has a tensile modulus 2.46 GPa and density 1.10 g/cm³ after being cured. For characterizing sound absorption efficiency of the samples, we perform the measurement in an impedance tube with a square cross section using the four-microphone method as is shown in Fig. 1(d).

Fig. 1. (a) Supercell in a rectangular lattice consisted of four MTVMA units. The lattice constants along $x$ and $z$ directions are $L/4$ and $L$, respectively. (b) Close sectional view of a single MTVMA unit. It transits from the minimum position ($\delta = 0\text{mm}$) to the maximum position ($\delta = 30\text{mm}$) by adjusting the slider. To demonstrate the details inside, the structure is rotated and the cover is removed. (c) Sectional schematic of the MTVMA on the $yz$-plane. (d) Experimental setup for acoustic measurement. The square cross-section of the impedance tube is $147 \times 147 \text{mm}^2$ and a
fabricated sample is placed in the impedance tube, and we adopt the four-microphone method for all the measurements.

In order to adjust the slider to reconstruct acoustic metamaterials, the relationship between tunable frequency and MTVMA geometry parameter has been investigated. All simulations are performed with a commercial finite-element method (FEM) software COMSOL Multiphysics (see supplementary material for setup details). Among them, \( d_{\text{chan}} \), \( d_{\text{slit}} \), \( a \), \( b \) are key parameters that have major impact on the absorption frequency and absorption rate. Among these parameters, we chose the parameter \( a \) which has a larger adjustable range and a significant influence on the sound absorption frequency as the adjustment parameter. Therefore, the parameter \( a \) is considered while maintaining the other parameters \( (b = 40 \text{ mm}, \ d_{\text{chan}} = 1.4 \text{ mm}, \ d_{\text{slit}} = 1.4 \text{ mm}, \ d_{\text{wall}} = 2 \text{ mm}) \). The absorption spectrum of parameter \( a \) is shown in Fig. 2(a). The red strip in the color map highlights the shift of the resonance of the MTVMA unit. As the length \( a \) is increased, the resonance shift from 500Hz to 300Hz towards low frequency and the absorption peak increases. The energy of human voice starts to become significant when the frequency is higher than 300 Hz, and low frequency (< 500 Hz) is difficult to be absorbed by conventional acoustic absorbers. Therefore, it is important to realize an acoustic metamaterial absorbers which can be adapted in the frequency window. The cavity is designed to allow the movement of the back plate of the cavity to adjust its volume so that the sound absorption frequency of the cavity moves between 300 Hz and 500 Hz. With the slider whose movement is characterized by the parameter, the parameter \( a = a_0 + \delta \), where \( a_0 = 40 \text{ mm} \), and the moving range of \( \delta \) is 0-30 mm. Two extreme configurations are considered, in which the minimum \( \delta = 0 \text{ mm} \) (\( a = 40 \text{ mm} \)) and the maximum \( \delta = 30 \text{ mm} \) (\( a = 70 \text{ mm} \)), respectively. In both configurations, \( b = 40 \text{ mm} \), \( d_{\text{chan}} = 1.4 \text{ mm} \), \( d_{\text{slit}} = 1.4 \text{ mm} \). The absorption spectra of the two extreme configurations are shown in Fig. 2(b). The experiments (solid line) and simulations (dashed line) achieve a favorable agreement. We also compare their performance with a commercial sound-absorbing foam (Basotect G+, BASF), which
is cut to the same occupied volume of the absorber. It is clear that, around the working frequencies, the absorber generally has an absorption significantly better than the foam. Therefore, it shows that with the movement of the slider, the frequency of the absorption peak is shifted sensitively while maintaining efficient absorption. The efficient ventilation is also maintained, as we will discuss below.

![Simulated spectra of absorption as a function of frequency and geometric parameter $a$.](image1)

![Experimental measurement (dashed lines) and simulation (solid line) absorption spectra of the MTVMA units.](image2)

![Simulated acoustic pressure field maps on cross section $y=0$ for $\delta=0$ mm and $\delta=30$ mm as the frequency is at resonance (514 Hz and 349 Hz), respectively.](image3)

![Samples configured to $\delta=0$ mm and $\delta=30$ mm in experiments.](image4)

Fig. 2. (a) Simulated spectra of absorption as a function of frequency and geometric parameter $a$. (b) Experimental measurement (dashed lines) and simulation (solid line) absorption spectra of the MTVMA units. For $\delta=0$ mm (blue solid line and cyan dashed line), $a=80$ mm, $b=40$ mm, $d_{\text{chan}}=1.4$ mm, $d_{\text{slit}}=1.4$ mm. For $\delta=30$ mm (red solid line and orange dashed line), $a=140$ mm, $b=40$ mm, $d_{\text{chan}}=1.4$ mm, $d_{\text{slit}}=1.4$ mm. (c), (d) Simulated acoustic pressure field maps on cross section $y=0$ for $\delta=0$ mm and $\delta=30$ mm as the frequency is at resonance (514 Hz and 349 Hz), respectively. At the resonant frequencies, the acoustic pressures inside the cavities for both configurations exhibits strong enhancement. The insets show photographs of the sample configured to $\delta=0$ mm and $\delta=30$ mm in experiments, respectively.
The sectional views of acoustic pressure fields for the two extreme configurations ($\delta = 0$ mm and $\delta = 30$ mm) of the MTVMA are plotted, as shown in Fig. 2(c) and Fig. 2(d), respectively. The pressure amplitude at their resonances (514 Hz and 349 Hz) are shown. In the narrow channels, the sound energy is converted into heat and dissipated under the action of air friction, which is stimulated by the large pressure differences between the inside cavities and outside environment. The slit in the pipe makes the upper and lower resonant cavities form a weak coupling, and the upper and lower cavities support identical eigenmodes. Such conditions ensure that the absorption peaks of the two cavities are coalesced rather than split due to radiation couplings\textsuperscript{36}, so that the total absorption rate at resonances exceeds 50\%, as we will discuss below using an effective model.

Fig. 3. (a) Schematic of the ventilation characterization system, which measures wind velocities. The inset indicates the nine positions at the tube outlet where the air flow velocities are recorded and averaged. (b) Experimental measurements (colored scatters) and their linear fittings (colored lines) for air velocities with and without the
samples, while the slider is positioned at different positions. The fitted slopes give the wind velocity ratios which characterize the ventilation performance.

Further, to investigate the ventilation performance of the MTVMA units with movement of the slider, we characterize their wind velocity ratios, defined as the measured ratios of the air velocities with and without the samples. The measurement instruction is shown in Fig. 3(a) and the sample is fixed in the middle of the aluminum tube when the air velocity with sample is measured. The electric fan is fixed at the inlet of the aluminum tube and the anemometer is fixed at the outlet. The sample is take out from the tube when the air velocity without sample is measured. We then take averages of the measurements for each configuration, as we measure at nine different positions of the outlet as indicated in the inset in Fig. 3(a). We then perform linear fittings to extract the wind velocity ratios while the slider is positioned at different positions. The results from measurement of air velocities are summarized in Figs. 3(b)-3(d). It can be seen that the linear fittings give efficient wind velocity ratios which are generally around 69%. Therefore, the high-efficiency ventilation of the MTVMAs is validated and also guaranteed during tuning their working frequencies.
Fig. 4. (a) Schematic of the effective model which describes the acoustic performance of the MTVMA. (b) Absorption spectra for $\delta = 0$ mm and $\delta = 30$ mm from simulations and the effective model, respectively. (c) The ratio $\kappa_c/(\eta_l+\eta_r)$ versus slider position $\delta$, plotted as orange scatters. The dashed line indicates the critical value $1/\sqrt{3}$. The model parameters $\eta_l$, $\eta_r$, and $\kappa_c$ are retrieved from numerically calculated eigenfrequencies of the MTVMA at different slider positions.

After these experimental validations, now we employ an effective model of coupled lossy oscillators to understand the high-efficiency absorption mechanism of the MTVMA$^{38}$. In fact, an absorption unit can be modeled as a pair of coupled lossy oscillators, as shown in Fig. 4(a), with the effective mass $m$ and the effective stiffness $k$. The radiation loss and the thermal loss are modeled as the damping $\eta_r$ and $\eta_l$, respectively. The dynamic equation of the two oscillators can be written as

$$m\frac{d^2}{dt^2} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} + \begin{bmatrix} \eta_l + \eta_r & i\kappa_c \\ i\kappa_c & \eta_l + \eta_r \end{bmatrix} \frac{d}{dt} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \end{bmatrix},$$

(1)
where $y_1$ and $y_2$ are vibration displacements of the oscillators in the effective model, with $F_1$ and $F_2$ denoting the forces on them, and $i\kappa_c$ denotes their radiation coupling. These model parameters can be retrieved from the eigenfrequency simulations, and they obviously depend on the slider position $\delta$. We assume the $e^{-i\omega t}$ time-harmonic convention, and after similar but cumbersome procedures\textsuperscript{36}, the absorption coefficient in the effective model can be expressed in the frequency domain as (see supplementary material for derivation details)

$$A = \frac{2\eta_0 \eta_c^0 (1 + |Y_{21,0}|^2)}{\eta_0^2 \left[ \frac{\omega}{\omega_0} - \frac{\omega}{\omega_0} + 2 \frac{\text{Im}(\eta_0 + i\kappa_c Y_{21,0})}{\eta_0} \right]^2 + 4(\eta + \text{Re}(\eta_c + i\kappa_c Y_{21,0}))^2},$$

(2)

with the parameter

$$Y_{21,0} = \frac{2i\kappa_c}{-2(\eta_0 + \eta_c) + i\eta_c \left( \frac{\omega}{\omega_0} - \frac{\omega}{\omega_0} \right)}.$$

(3)

The parameters $\omega_0 = \sqrt{k/m}$ is the resonance angular frequency, $\eta_0 = 2\sqrt{km}$ is the critical damping coefficient, and $\eta_c^0$ is an auxiliary parameter, referred to as the reference radiation loss. To validate the model, we retrieve the model parameters $\omega_0$, $\eta$, $\eta_l$, and $\kappa_c$ from eigenfrequency simulations for different $\delta$, and compare the fitted absorption spectra with those from full-wave simulations, as plotted in Fig. 4(b). It is seen that the fitted spectra capture the essence of the numerical results, and hence we can safely describe the ventilated absorber with the effective model. As previously demonstrated\textsuperscript{36}, in order to achieve an efficient absorption, the model parameters need to satisfy that

$$\kappa_c < \frac{\eta_l + \eta_c}{\sqrt{3}}.$$

(4)

We retrieve the model parameters from full-wave simulations, and plot the ratio $\kappa_c/(\eta_l + \eta_c)$ in Fig. 4(c). It is clear seen that the values of the ratio are significantly smaller than the critical value $1/\sqrt{3}$ within the designed range of the slider position $\delta$. Therefore, during the movement of the slider, it is guaranteed that the radiation
coupling between the two resonators in an absorption unit is weak enough, such that
the absorption peaks from the two resonators coalesce, resulting in an efficient
absorption. This is largely attributed to the very small slit width \( w_{\text{slit}} \) in our designed metamaterial.

Fig. 5. (a) Supercell in a rectangular lattice that is consisted of four MTVMA units
under the oblique incidence and the angles of incidence are defined as \( \phi \) and \( \theta \) in inset.
\( \mathbf{k} \) represents the wave vector. (b)–(d) Simulated spectra of absorption under oblique incidence and the angles are defined as \( \theta \) varying, \( \phi = 0 \) (b), \( \phi \) varying, \( \theta = 0 \) (c), and \( \theta = \phi \) varying (d), respectively.

Finally, we investigate the influence of oblique incidence, and the absorption spectra under different incident angles are calculated from full-wave simulations. The
The direction of the incident wave is characterized by the incidence angles labeled as $\theta$ and $\phi$, shown in Fig. 4(a). We also simulated the absorption of MTVMA under oblique incidence with varying $\theta$ and $\phi$, and the results are shown in Figs. 4(b) and 4(c), respectively. The absorption decreases slightly with the incident angles $\theta$ and $\phi$ changing from normal incidence to large oblique incidence ($> 70^\circ$). This is due to the deep subwavelength profile of the MTVMA ($\sim 1/8$ wavelength at 350 Hz) which makes the structure relatively insensitive to the incident angle. We also explored the absorption spectrum of MTVMA when $\theta = \phi$. It can be seen that the MTVMA still retains the characteristics of the efficient absorption with ventilation under oblique incidence.

**Discussion**

To conclude, in this work, we propose and experimentally demonstrate an MTVMA, which is an ultra-open ventilated metamaterial absorber that can be manually adjusted so as to change the working frequency after being fabricated, meanwhile retaining the desired high-performances at low frequencies. The MTVMA is comprised of weakly-coupled split-tube resonators, and we can shift the working frequency of the MTVMA within the important frequency window of 300-500Hz by simply sliding the sliders. The key to the efficient absorption and ventilation of the MTVMA units is the weak coupling between the two split tube resonators, which leads to the coalescence of the absorption peaks of the symmetric mode and the anti-symmetric mode of the two resonators. Moreover, the tunability of their sound absorption frequencies lies in the sensitive dependence of the resonance frequencies on the cavity geometries that are adjusted by the shift of the sliders. The MTVMA breaks the limit of the previous ventilated sound-absorbing metamaterials that the absorption frequency cannot be changed after being fabricated.

Therefore, the MTVMA has promising application potential in various noise control scenarios, such as duct ventilation and engine systems, since the designs need to handle a variety of noises and ventilation performance is also one of the most
concerns. Moreover, the MTVMA paves the way for the development of automatically adjustable sound-absorbing ventilated metamaterials in the future. In addition, the working principle in this work is also suitable for other background fluids.

**Supplementary Material**

See supplementary material for the setup details of simulations in COMSOL Multiphysics, and the derivation of the absorption in the effective model.

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**Data Availability**

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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