Ultra-broadband acoustic absorption of a thin microperforated panel metamaterial with multi-order resonance

Chong Rui Liu, Jiu Hui Wu*, Zhengrui Yang, Fuyin Ma

School of Mechanical Engineering & State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China

A R T I C L E   I N F O

Keywords:
Ultra-broadband acoustic metamaterial Low-frequency broadband sound absorption Micro-perforated panel High-order absorption peaks

A B S T R A C T

Aiming at poor efficiency of the traditional materials in low-mid frequency sound absorption and its narrow bandwidth, we present an ultra-broadband acoustic metamaterial that can achieve near-perfect continuous absorption within 380 Hz–3600 Hz with a thickness of only 7.2 cm. Its basic cell is constructed by turning the original neck of a Helmholtz resonator into multiple smaller ones, and the neck panel becomes into a microperforated panel (MPP). By coupling the characteristics of the cavity's multi-order resonance and the MPP's broadband absorption, the cell's high-order impedances can be tuned to more match that of the air medium. The cell can therefore obtain multiple excellent high-order absorption peaks besides the original one; meanwhile all the peaks can become broader resulting from the larger energy leakage rate. On this basis, a subwavelength 12-cell sample is obtained of which the absorption band is broadened almost 100% by the high-order peaks and has an average absorption coefficient above 90%. Characterized by the extraordinary absorption performance, thin thickness, and easy-fabricated structure, this proposed metamaterial has great potential in noise control engineering applications.

1. Introduction

Today noise is considered as a serious environmental and social problem, and has been one of the four major environmental pollutants [1]. In particular, the low-frequency noise can result in many health problems, such as hearing loss, headaches, sleep disturbance, and inattention [2]. Thus, the effective methods to reduce low-frequency noise are urgent needs to protect the acoustical environment. The traditional microperforated panels (MPP) [3–5] and porous materials [6–8] are two common conventional materials for sound absorption, but they both show poor absorption performances for low-frequency sound due to the weak energy dissipations.

In recent years, acoustic metamaterials have been the focus of research interest owing to the novel properties not observed in nature. Although excellent low-frequency absorption has been obtained in some studies [9–16], these metamaterials can only demonstrate narrow band performances which have limited the wide engineering applications. Until now, some works have achieved broadband absorption to some extent by introducing multiple detuned cells with different peaks [17–36]. Fabry-Pérot (FP) cavity and Helmholtz Resonator (HR) are two main types utilized as the basic cell of the coiled metamaterials, wherein the FP-type structure's peak has a higher frequency than that of HR-type structure due to the loss of the “neck” mass. Hu et al. [17] reported an 18 cm-thick structure, comprised of 6 coiled FP cavities, which achieved near-perfect absorption performance within 100 Hz–200 Hz. Chen et al. [18] proposed a subwavelength structure in which two axially coupled FP cavities in series were coiled into a layer perpendicular to incident waves for reducing the sample thickness, and a good sound absorption performance was obtained within an extremely low-frequency range. Jiménez et al. [19] addressed a perfect and broadband absorption absorber with deep-subwavelength thickness, namely rainbow-trapping absorber, in which the panels were composed of multiple HRs with graded dimensions. Wu et al. [20] designed a hybrid sound-absorbing metamaterial based on a microperforated panel (MPP) and coiled-up FP cavities, and by integrating two different cells, an near-perfect absorption band within 355 Hz and 470 Hz was achieved under a thickness of 5 cm. However, in most of current researches, the absorption band was comprised of only the first-order peak of single cell. The bandwidth can actually be further broadened sufficiently by introducing high-order peaks, which is of great significance for the project. Very recently, an absorption structure including some high-order peaks, composed of 16 coiled-up FP cavities, was presented by Yang et al. [21] with a thickness of 10.36 cm, in which a near-perfect flat absorption spectrum in the range of...
400 Hz–3000 Hz was obtained. In our earlier works [22,23], we proposed a new kind of multi-order HR absorption mechanism which is achieved by inserting some separating plates with a small hole into the interior of a HR. Based on this, an 8 cm-thick absorber was designed with a near-perfect absorption band within 400 Hz–2800 Hz, but its internal structure was a little complicated and hard to be manufactured efficiently.

In this work, we further report an ultra-broadband, thin and easily-fabricated metamaterial with multi-order peaks in low-mid frequency range, of which the basic cell is composed of a single MPP and a coiled cavity. By combining the characteristics of the cavity’s multi-order resonance and the MPP’s broadband absorption, this MPP structure gains not only multiple excellent high-order peaks, but also broader bandwidth for each peak; therefore the total absorption band can be further broadened. Compared with those FP-type structures, this MPP structure’s peaks are all moved to lower frequencies with the same cavity because the total acoustic mass is increased by the MPP. Finally, a multi-cell metamaterial with a deep-subwavelength thickness of only 7.2 cm is obtained which exhibits a continuous excellent absorption band within 380 Hz–3600 Hz with an average absorption coefficient above 90%.

The paper is organized as follows: in Section 2, the unit structure and absorption performance of the proposed metamaterial are first introduced. The sound absorption coefficient and broadband absorption mechanism are then analyzed by the theoretic method and the finite element (FE) simulation; in Section 3, the effects of the typical parameters, such as the hole diameter, cavity depth and absorption area ratio, on the absorption performances are then investigated in detail; in Section 4, the metamaterial unit with excellent broadband absorption is achieved and tested by the corresponding experiment. Finally, several conclusions are drawn in Section 5.

2. Ultra-broadband absorption mechanism in a metamaterial unit

2.1. Structure of the metamaterial unit

The proposed structure is constructed by replacing the neck panel of a HR structure with a micro-perforated panel without changing the structural dimensions, as shown in Fig. 1(a) and (b), respectively. The HR structure with \( w_1 = 34 \text{ mm}, \ w_2 = 34 \text{ mm} \) and \( l = 12 \text{ mm} \) is composed of three parts: a coiled frame, a face panel and a neck panel. As the HR neck, a small hole with diameter \( d_0 = 1.6 \text{ mm} \) is positioned at the center of the neck panel with side length \( a = 10 \text{ mm} \). The thickness of the neck panel is \( h_0 = 1 \text{ mm} \), as well as the frame and the face panel. The MPP with thickness \( h = 1 \text{ mm} \) in Fig. 1(b) is perforated by smaller holes with number \( n = 25 \) and diameter \( d = 0.6 \text{ mm} \), and the perforation rate is about \( \alpha = 7.1\% \). The sound wave path is coiled and extended by the frame, of which the cross-sectional area is \( S_x = a \times b = 10 \text{ mm} \times 10 \text{ mm} \). The total length is \( l_0 = 98 \text{ mm} \). The side length of the sound channel inside the frame is \( c = 32 \text{ mm} \). The sound wave is incident to the surface along the negative direction of the \( z \) axis. Here the absorption area ratio is defined as \( \eta = S_x / S_0 \), where \( S_0 = w_1 \times w_2 \) is the incident surface area.

The sound absorption coefficients of the HR structure and MPP structure are shown in Fig. 1(c), and the comparison between the theoretical calculations and the FE simulations shows a good agreement. It can be observed that the HR structure has a low-frequency near-perfect absorption peak at \( f_1 = 450 \text{ Hz} \), of which the structure thickness is only \( 1/62 \) of the corresponding wavelength. It also gains two high-order peaks in higher frequency range, but which can almost be neglected due to the low absorption coefficients. In contrast, although the first peak of the MPP structure is moved to higher frequency \( f_2 = 695 \text{ Hz} \), its peak bandwidth (absorption coefficient \( \alpha > 0.7 \)) is increased to \( \Delta f_2 = 98 \text{ Hz} \) which is about two times of the HR bandwidth \( \Delta f_1 = 47 \text{ Hz} \). Besides, the MPP structure obtains two more excellent high-order peaks, which can be used to achieve a continuous absorption band. From the perspective of broadband absorption, the MPP structure obviously has much greater advantages than the HR structure.

2.2. Calculation of sound absorption coefficient

A. Theoretical calculation

When an acoustic wave is incident to an absorption structure with an inhomogeneous surface, there exist the evanescent waves along the surface which can affect the absorption performance. Since the average impedance method is not rigid enough, an approach, similar to the plane wave expansion method, is used here to consider the effects of the surface evanescent waves and predict the absorption coefficient as accurately as possible. In particular, when the structure comprised of multiple detuned cells, this kind of surface evanescent waves can bring about mutual couplings between the cells which have some effects on the absorption.

The unit surface impedance \( Z_0(\text{unit: Pa s/m}^3) \) in Fig. 1 (b) can be expressed as

\[
Z_0 = Z_\text{fr} + Z_\text{c},
\]

where \( Z_\text{fr} \) and \( Z_\text{c} \) are the impedances of the MPP and the cavity, respectively. The relative specific surface impedance \( z_\text{s}(\text{unit: 1}) \) is therefore obtained as

\[
z_\text{s} = \frac{S_0}{\rho_0 c_0} \varphi_0 - \varphi_0 \rho_0 c_0
\]

where \( \varphi_0 = 1.25 \text{ kg/m}^3, \ c_0 = 343 \text{ m/s} \) are the density and sound speed of the air. It can be seen that the relative specific impedance \( z_\text{s} \) is proportional to the incident surface area \( S_0 \) when the impedance \( Z_0 \) is kept constant.

The MPP’s impedance \( Z_\text{MPP} \) can be calculated from the Euler equation as [3].
\[ Z_m = \frac{j\omega \rho}{nS_0} \left( h\left[1 - \frac{2B_0(x_j - \sqrt{\gamma})}{(x_j - \sqrt{\gamma})B_0(x_j - \sqrt{\gamma})}\right] ^{1 + 0.85d} + \frac{\sqrt{\gamma} \mu_k}{nS_0d} \right), \]  
\[ \text{where } \omega \text{ is the area of a single hole, } \gamma = \frac{\mu_0\omega}{4\pi} \text{ is the perforation constant, } B_0 \text{ and } B_1 \text{ are the zeroth and first order Bessel function of first kind, respectively, and } \mu = 1.8 \times 10^{-5} \text{ Pa} \text{s is the dynamic viscosity coefficient of the air.} \]

The surface impedance of the coiled cavity \( Z_s \) can be obtained as
\[ Z_s \approx -j\omega \rho \cos(k_0 l_0)/S_0, \]  
\[ \text{where } Z_s^e = \frac{\rho c_0}{\omega \rho} C_i^e \text{ and } k_i^e = \omega \sqrt{\gamma} C_i^e \text{ are the effective characteristic impedance and effective wavenumber of the air inside the cavity, respectively. According to the visco-thermal acoustic theory [37], the effective density } \rho^e \text{ and effective bulk compressibility } C_i^e \text{ are given by}\]
\[ \rho^e = \frac{\rho - \rho_0^2}{\nu a^2} \left( \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \left[ \alpha m^2 \alpha n^2 (\alpha m^2 + \beta n^2) \right] \right)^{-1}, \]
\[ C_i^e = \frac{1}{\rho^e} \left( 1 - \frac{\nu a^2}{\nu^2} \right) \left[ \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \left[ \alpha m^2 \alpha n^2 (\alpha m^2 + \beta n^2) \right] \right]. \]
\[ \text{where } \alpha = (m + 1/2)\pi/a \text{ and } \beta = (n + 1/2)\pi/b, \text{ } \nu = \mu/\rho_0 \text{ and } \nu' = \nu/\rho_0. \]
\[ C_i = \frac{1}{\rho^e} \left( 1 + \frac{\nu' a^2}{\nu^2} \right) \left[ \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \left[ \alpha m^2 \alpha n^2 (\alpha m^2 + \beta n^2) \right] \right]. \]

Based on the surface impedance, the absorption coefficient is then calculated with an approach that is similar to the plane wave expansion method [33]. Assuming small-amplitude disturbance with time dependence \( e^{j\omega t} \), an arbitrary plane wave is incident to the structure surface, the sound field \( p(x, y) \) in front of the surface can be expressed as
\[ p(x, y) = p_i(x, y, z) + p_s(x, y, z), \]
\[ p_i(x, y, z) = \sum_{m, n}^{\infty} \frac{A_{mn}}{k_0} e^{j(k_x x + k_y y)} e^{j\omega t}, \]
\[ p_s(x, y, z) = \sum_{m, n}^{\infty} k_{mn} A_{mn} e^{j(k_x x + k_y y)} e^{j\omega t}, \]
\[ a(\theta, \varphi) = 1 - \sum_{m, n \neq 0} \left| \frac{A_{mn}}{P_1} \right|^2 \frac{\kappa_{mn} k_{0}}{k_{z}^0}. \]
\[ \text{The normal incidence absorption coefficient can be obtained with } \theta, \varphi = \theta', \varphi'. \]
\[ \text{B. Finite element simulation} \]

The numerical element simulation is developed by using the commercial FEM package COMSOL Multiphysics™ 5.2, in which the Acousto-Thermoacoustic interaction module is adopted, and the viscous friction and thermal conduction both included. A normally incident plane wave with unit amplitude is applied perpendicularly on the unit surface along the negative direction of the \( z \) axis. The pressure acoustic model is adopted to describe the outside free air, and the thermoacoustic model is for the inside confined air. Hard boundaries are applied for all the cavity walls due to the much larger impedance than that of air, and periodic boundaries are chosen on both sides of the unit. In order to characterize the visco-thermal losses precisely, the boundary layer meshes with 6 layers are applied on the walls of MPP holes and cavities, and the thickness of each layer is \( d_v/4 \), where \( d_v = \sqrt{2 \mu/\rho_0 \omega} \) is the thickness of the viscous boundary layer.

\[ \text{2.3. Broadband absorption mechanism of MPP structure} \]

It is obvious that compared with HR structure, the absorption band in MPP structure can be further broadened by the broader single bandwidth and high-order peaks without introducing more detuned cells. To explain the broadband absorption mechanism qualitatively, the structure’s relative specific impedance \( z_s = x_s + jy_s = r_s + j(\omega m_s - 1/\omega c_s) \) is further investigated through the surface acoustic impedance and capacitance, respectively. The relative specific reactance \( r_s \) consists of two parts: the resistance of MPP \( r_{sp} \) and that of the cavity \( r_{sc} \), as
\[ r_s = r_{sp} + r_{sc}, \]
\[ r_{sp} = \frac{32\mu h}{\rho_0 c_0^2 \eta \pi^2 k_s^2}, k_s = \sqrt{1 + \frac{\eta^2}{32} \frac{32}{\pi^2}}, \]
\[ r_{sc} = \frac{\Re(\frac{Z_s}{\rho_0 c_0^2} \eta)}. \]

The analytic formula of the resistance \( r_{sc} \) cannot be given here due to the complicated expression of \( Z_s \), but which has no influence on the later analysis of the absorption property. Similarly, the relative specific mass \( m_s \) is composed of MPP’s mass \( m_{sp} \) and the cavity’s mass \( m_{sc} \), as
\[ m_s = m_{sp} + m_{sc}, \]
\[ m_{sp} = \frac{h}{c_0^2 \eta}, k_m = 1 + \frac{1}{\sqrt{9} + \chi^2} + 0.85 \frac{d}{h}, \]
\[ m_{sc} = \frac{1}{3c_0^2 \eta}. \]

The relative specific capacitance \( c_s \) results from the cavity and can be expressed as
\[ c_s = \frac{c_0}{l_0}. \]
\[ \text{A. Broader single peak bandwidth} \]

Taking the first peaks as example here, the variation of single peak is firstly investigated through the surface acoustic impedance and complex frequency analysis. For a clear comparison, the absorption coefficients of the first peaks are shown in Fig. 2(a), and the corresponding relative specific impedances illustrated in Fig. 2(b). It can be

\[ \text{3.} \]
observed that the two structure’s relative specific reactances \( y \) cross zero at the peak frequencies \( f_1 = 450 \) Hz and \( f_2 = 695 \) Hz, indicating that the structures are in resonance states; the corresponding relative specific resistances are \( r_1 = 1.01 \) and \( r_2 = 1.03 \), which basically meet the second impedance matching condition, so that both peaks can achieve almost 100\% absorption. In order to always keep the resistance \( r_s \) matched with that of the air medium, it can be known from equation (11a), the perforation rate \( \sigma \) should be increased with the decrease of the hole diameter \( d \) when the resistance \( r_s \) is kept unchanged. In the meantime, the relative specific mass \( m_{sp} \) and \( m_p \) are decreased by the increased perforation rate \( \sigma \) from equation (12). The relative specific capacitances \( c_s \) is just determined by the cavity depth \( l_0 \) and can stay constant in this progress. Therefore the peak in MPP structure is shifted to higher frequency because the mass is decreased and capacitance unchanged, i.e. \( m_{s2} < m_{s1} \) and \( c_{s2} = c_{s1} \). However, the acoustic impedance characteristics in Fig. 2(b) fail to present the information about the peak bandwidth intuitively.

We further conduct the complex frequency analysis to more fully characterize their absorption performances, as shown in Fig. 2(c) and (d). The reflection coefficient can be plotted on the complex frequency plane by replacing the wavenumber as \( k = k_r + jk_i \), where \( k_r \) is the intrinsic wave number and \( k_i \) is the imaginary wave number. In general, the reflection coefficient exhibits a complex conjugate zero and pole in a lossless system. As the loss is introduced into the system, the zero and pole will be shifted down along the imaginary axis. When the zero falls on the real frequency axis (the black dash dot line with \( f_1 = 0 \)), the intrinsic losses perfectly balance the energy leakage of the system and therefore perfect absorption can be obtained, which is called critical coupling condition. The system is under-damped (over-damped) with \( k_r \) unchanged, i.e. \( m_{s2} = m_{s1} \) and \( c_{s2} = c_{s1} \). However, the acoustic impedance characteristics in Fig. 2(b) fail to present the information about the peak bandwidth intuitively.

In fact, the peak bandwidth variation can also be explained by the quality factor \( Q \) in this kind of single-degree-of-freedom structure. Considering the structure’s resonant nature, the peak bandwidth \( \Delta B \) can be expressed approximately by quality factor \( Q \) as \( \Delta B/|f_1| = 1 \), where \( Q = \omega/m_0/r_0 \). After simplification, the peak bandwidth is obtained as \( \Delta B = \sigma/2\pi m_0 \). Therefore the bandwidth is \( \Delta B_2 > \Delta B_1 \) due to \( r_1 < r_2 \) and \( m_{s2} < m_{s1} \).

B. High-order peaks under the influence of anti-resonance modes

The specific properties of the high-order peaks and the internal causes are investigated by the surface acoustic impedance, as shown in Fig. 3. Fig. 3(a) shows the relative specific resistances of the two structures (MPP and HR), the two panels and the cavity. It can be observed that the two structures have the almost equal first-order resistances, but the high-order resistances of HR structure \( r_{s1} \) are 4.75 and 19.55, respectively, which are much larger than those of MPP structure (i.e. 1.67 and 2.31) and go against the impedance matching conditions seriously. Therefore, the high-order peaks of HR structure nearly lost the absorption ability, while those of MPP structure can drop slowly and still exhibit good performances.

This performance difference between two structures can be explained from the impedance properties of the panel and cavity. It can be seen that the resistances \( r_{sp} \) of MPP panel and HR panel both have a slow growth from 100 Hz to 4000 Hz, which are just increased from 0.6 to 2.49 and 1.83, respectively. However, the cavity resistance \( r_c \) has a sharp increase at some frequencies and can be regarded as infinity, but just a small value at other frequency ranges, which is resulting from its anti-resonance modes. The frequencies of anti-resonance modes are called anti-resonance points \( (f = 1780 \)Hz and 3570 Hz), as shown in Fig. 3(b), of which the specific properties will be explained later based on Fig. 3(c)-(f). Generally, it can be concluded that the MPP (HR) structure’s resistance \( r_s \) is governed by the cavity resistance \( r_c \) in the
vicinity of anti-resonance points, and dominated by the panel’s resistance \( r_m \) at other frequency ranges. It can therefore be seen from Fig. 3(a) that, compared with HR structure, the high-order peaks of MPP structure are less affected by the anti-resonance modes, and therefore their resistances are increased slowly.

Fig. 3(b) presents the relative specific reactances \( \chi \) of the two structures (MPP and HR) and the cavity. It can be seen that since the anti-resonance modes are just caused by the cavity, the MPP and HR structures obtain the same anti-resonance points as the cavity. In contrast, the reactance zeros, i.e. \( \omega m_s - 1/\omega c_s = 0 \), are evidently influenced by the masses of the panels. The relative acoustic masses \( m_s \) are 4.55e-4, 1.65e-4 and 0.94e-4 in HR structure, MPP structure and cavity, respectively, which are plotted with dash dot lines. It can be observed that the high-order reactance zero points move gradually to lower frequencies, and approaching the anti-resonance points with the increase of the mass \( m_s \). As a result, the influences of the anti-resonance modes on the corresponding absorption peaks and their resistances are increasing by degrees, as shown in Fig. 3(a). Therefore it can be concluded that the absorption properties of the high-order peaks are mainly determined by the acoustic mass \( m_s \) of the panel which should be adjusted carefully to balance the whole performance of the absorption structure.

Fig. 3(c)–(f) present the MPP structure’s pressure and velocity fields at the first absorption peak \( f = 695 \) Hz and the first anti-resonance point \( f = 1780 \) Hz, respectively. It can be observed in the Fig. 3(c) that the sound pressure of the incident surface is about \( p_1 = 1.1 \) Pa, nearly equal to the incident sound pressure of \( p_0 = 1 \) Pa, which means that all the incident sound waves are nearly absorbed without reflection. The blue arrows, representing the logarithmic particle velocities, show that the velocity inside the small holes is much greater than that inside the cavity. Fig. 3(e) illustrates the specific velocity values, wherein the velocity inside the holes is up to \( v_3 = 0.6 \) m/s while that inside the cavity is almost zero. It can be concluded that the whole incident energy is nearly dissipated by the panel holes, and the cavity can be equivalent to a lossless spring with only acoustic capacitance. On the contrary, the incident surface has a pressure of \( p_2 = 2 \) Pa at the anti-resonance point in Fig. 3(d), implying that all the incident sound waves are nearly reflected. As shown in Fig. 3(f), the corresponding velocity is just \( v_2 = 5e-3 \) m/s, which is much smaller than \( v_1 = 0.6 \) m/s. Therefore it can be verified that the acoustic impedance \( z_2 = p_2 / v_2 \) at the anti-resonance point is much greater than that at absorption peak \( z_1 = p_1 / v_1 \). Considering the system has tiny vibration amplitude and remains almost stationary, it can be regard as a rigid wall with infinite impedance.

3. Parameter effects on the absorption performances of MPP structures

3.1. Effects of the hole diameter \( d \)

Fig. 4(a) shows the structure’s absorption performances with the diameter \( d \) varied as 1 mm, 0.6 mm, 0.4 mm and 0.2 mm. It can be known from equations (11) ~ (12) that the variation of the diameter \( d \) can change the structure’s relative specific acoustic resistance \( r_s \) and acoustic mass \( m_a \) simultaneously, and therefore other parameters should also be regulated to make the first peak always achieve 100% absorption. Here the hole number \( n \) is adjusted as 4, 25, 100 and 500 \( (h = 0.4 \) mm), and the corresponding resistances are always \( r_s = 1 \) and the masses \( m_a \) are 2.75e-4, 1.65e-4, 1.31e-4, and 1.06e-4, respectively. It can be concluded that the mass \( m_a \) is reduced by the decrease of the diameter \( d \) when the resistance \( r_s \) is kept constant. It can be observed from Fig. 4(a) that owing to the decreased mass, all the peaks move to higher frequencies and the corresponding peak bandwidths are broadened when the diameter is reduced from \( d = 1 \) mm to 0.2 mm. More specially, the high-order peaks are enhanced obviously with the decrease of the diameter because the influence of the anti-resonance mode is getting weakened. When the diameter is \( d = 0.2 \) mm, the absorption coefficients of the high-order peaks have a very small drop, wherein the third-order peak can reach above 95% and the bandwidth is increased about as much as five times. It can be concluded that an appropriate reduction of the diameter can boost the structure’s high-order absorption performances in higher frequency range largely, which is very beneficial for the broadband absorption. The only disadvantage is that the peak can be shifted to higher frequencies, which is harmful for the low-frequency absorption situation.
Fig. 4. Effects of (a) the hole diameter \(d\) and (b) the total cavity depth \(l_0\) on the sound absorption coefficients.

3.2. Effects of the cavity depth \(l_0\)

Fig. 4(b) presents the effects of the cavity depth \(l_0\) on the absorption performances, and the depth \(l_0\) is selected as 250 mm, 150 mm, 100 mm and 60 mm, respectively. It can be seen that all the absorption peaks are shifted to lower frequencies with the increase of depth \(l_0\), and meanwhile the first peaks can always achieve perfect absorption. This variation of the peak frequency is caused by the gradually decreased effective stiffness of the cavity. In particular, more high-order peaks are obtained in the target frequency range with the depth increasing. For example, when the depth is \(l_0 = 250\) mm, the structure gains five high absorption peaks below 4000 Hz and the first peak frequency is as low as \(f = 300\) Hz, which is very beneficial for the achievement of the low-frequency broadband absorption.

3.3. Effects of the absorption area ratio \(\eta\)

With the peak number of each cell kept constant, the most effective way to further broaden the bandwidth is to increase the cell number \(n_0\) in a basic unit. It can be seen from Fig. 1(b) that the smaller the absorption area ratio \(\eta\) is, the more cells can be accommodated in the unit with cell number \(n_0 \approx 1/\eta\), hence the wider bandwidth can be achieved. However, different ratios \(\eta\) can bring about some variations on a single cell’s absorption performance.

Fig. 5(a) presents the absorption coefficients with different area ratios \(\eta\), and the diameter \(d\) is set as 0.3 mm, 0.4 mm, 0.6 mm and 0.7 mm, respectively. It can be observed that the first peaks can always reach about 100% absorption, while the second and third peaks gain almost 90% and 80% absorption, respectively. However, as the area ratio decreases from \(\eta = 1\) to \(\eta = 1/18\), the peak bandwidths become narrower and the peaks are shifted to higher frequencies gradually, which is not what we expect. For a clear demonstration, the specific performances of the first peak are illustrated in Fig. 5(b). The bandwidth is decreased from 540 Hz to 68 Hz, while the peak frequency is shifted from 460 Hz to 750 Hz. To explain the phenomenon qualitatively, the absorption coefficient can be obtained from equation (11) ~ (13), as

\[
\alpha = \frac{4r_s}{(1 + r_s)^2 + (\omega m_s - 1/\omega c_s)^2},
\]

and the bandwidth as well as the peak frequency can be obtained as

\[
\Delta B = \frac{3}{2\pi} \frac{1 + r_s}{m_{sp} + m_c},
\]

\[
f_0 = \frac{1}{2\pi} \sqrt{\left(\frac{c_0/\rho}{(m_{sp} + m_c)\eta}\right)}.
\]

It can be known from equation (15) that the relative specific resistance of the first peak is always \(r_s = 1\) with the decrease of ratio \(\eta\) to achieve 100% absorption. Based on this, it can be obtained from equation (12a) ~ (12c) that the relative specific mass \(m_{sp}\), \(m_c\) are both increased, while the mass \(m_{sp}\), \(m_c\) are decreased and constant, respectively. Finally, the variations of the bandwidth \(\Delta B\) and the peak frequency \(f_0\) can be explained by equation (15). It can therefore be concluded that the total bandwidth cannot be broadened significantly by the decreased ratio \(\eta\) because the single band becomes narrower in the meantime. It is unwise to increase the cell number blindly, because it can only increase the bandwidth to a certain extent, but bring about big difficulties of design and manufacture simultaneously.

4. The achievement of ultra-broadband absorption and experimental verification

To achieve ultra-broadband absorption, we further conduct the
design, fabrication and experimental characterization of a coiled metamaterial with multiple critically coupled cells. As shown in Fig. 6(a), the basic unit of the metamaterial is composed of 12 detuned cells, in which the orange cells (1,2), pink cells (3,4), green cells (5,6) and yellow cells (7–12) are provided with 4, 3, 2, 1 peaks, respectively. The numbers annotated in Fig. 6(a) from 1 to 12 denote the cells with first-order peak frequency from lower to higher. The basic unit has a length of $l_0 = 45$ mm, a width of $w_0 = 34$ mm and a thickness of $h_0 = 72$ mm. The MPP layer has a thickness of $h = 1$ mm and is perforated by the small holes with number $n = 25$ and diameters $d = 0.6$ mm. The cavity depths and first-order peak frequencies of the cells are illustrated in Fig. 5(b), from which it can be seen that the depths have a large span from $l_1 = 200$ mm to $l_{12} = 10$ mm, and therefore the frequencies can cover a broadband range from $f_1 = 380$ Hz to $f_{12} = 3380$ Hz.

The absorption coefficients are firstly predicted by above theoretical calculation and FE simulation, as shown in Fig. 6(c). It can be observed that the theoretical and simulated results have a good agreement, and an ultra-broad near-perfect absorption spectrum is obtained in the range of 380 Hz–3600 Hz with a mean absorption coefficient above 90% under a subwavelength thickness. The whole absorption band, which results in multiple near-perfect peaks and a high mean absorption coefficient. The cells’ peak resistances, dominated by MPP panel, are gradually increased with the frequency increasing, and therefore the zeros of the cells are moved below the real axis with the decrease of the cavity depth. The leakage rate (distance) between the zero and pole is getting wider with the increase of frequency, implying a broader peak bandwidth.

To verify the corresponding results, the sample shown in Fig. 7(a) is fabricated and then measured in a square acoustic impedance tube. The MPP panel is manufactured by the micro electrical discharge machining (MEDM) method and the cavity by the 3D printing technology with the acrylonitrile butadiene styrene (ABS) plastic. The sample therefore exhibits excellent mechanical stiffness and strength. The impedance tube has a side length of 50 mm, in which only the plane wave can propagate below 3200 Hz. The sample is installed at the end of the tube and measured with the standard two-microphone transfer function method [38], as shown in Fig. 7(b). Two 1/4 in. B&K Type-4958A condenser microphones are used to record the sound pressure, and a B&K Type-3160-A-042 data acquisition system is used to acquire the sound pressure. It should be noted that what we acquire from the measurement is the specific surface impedance of the sample, rather than the absorption coefficient, because the area of the tube (50 mm × 50 mm) is larger than that of the sample (45 mm × 34 mm). The sample is placed into a testing-frame which is used to fill the gap between the tube and the sample. The whole incident surface of the assembly is ensured to be flat; therefore the surrounding area of the sample can be regarded as the rigid wall and the influence of the gap is eliminated. The distances between the microphones and the sample surface are $s_1 = 100$ mm and $s_2 = 90$ mm, respectively. The absorption coefficient is then calculated through the measured specific surface impedance. Owing to the frequency limit of the test system, the experimental result here is presented below 3200 Hz. The sound absorption coefficients from the FE simulation and experimental measurement are shown in Fig. 7(c), from which it can be observed that the experimental result is basically in agreement with the predicted results. The experimental
result shows a better performance than the FE simulations in the low frequency range, which should be mainly ascribed to the energy dissipation of air itself and the rough edges of the small holes. It is noted that these two facts cannot yet be taken into account effectively in the current model. On the other hand, the absorption band has obvious fluctuations above 2000 Hz, which is mainly caused by the manufacturing errors of small hole diameters. Compared with the first-order peaks, a slight diameter discrepancy can actually have a larger influence on the frequencies of the high-order peaks, resulting in the discontinuous arrangement of the peaks.

5. Conclusions

In this study, we propose an ultra-broadband acoustic metamaterial with a near-perfect absorption spectrum in the low-mid frequency range of 380 Hz–3600 Hz, of which the thickness (7.2 cm) is reduced to the deep-subwavelength regime. The multi-order resonance of the cavity is the basis of this ultra-broadband absorption, of which the high-order impedance properties can be adjusted by the MPP to achieve more excellent high-order absorptions. The structure’s high-order impedances are more matchable with that of the air medium with the hole diameters’ decrease, and thus, multiple high-order peaks can be obtained with high absorption coefficients. Moreover, the single peak bandwidth becomes much broader in the meantime due to the decreased acoustic mass. The adjacent peaks can therefore have a major distance and the cells’ cavity depths have a larger decrease. As a result, the final broadband absorption structure can still have a thin thickness, although the first cell gains a larger cavity depth. In conclusion, the metamaterial can achieve extraordinary absorption performance compared with the traditional materials with the same thickness, and possess an easy-fabricated and lightweight structure simultaneously. This kind of MPP metamaterial will have broad application values in the noise reductions of rooms, plants, automotive industry and aerospace engineering.

CRediT authorship contribution statement


Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (NSFC) under Grant No. 51675401 and 51705395.

Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

References


