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Cite as: AIP Advances 9, 125226 (2019); https://doi.org/10.1063/1.5126807
Submitted: 05 September 2019. Accepted: 30 November 2019. Published Online: 20 December 2019

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ABSTRACT
A new hybrid-mechanism metastructure combined resonances of locally resonant scatterers and air cavities is proposed for broadband waterborne sound absorption. In the design, the locally resonant scatterers are embedded into the backing plate of a rubber layer with air cavities. The results demonstrate significant absorption improvement in the low-frequency range using the locally resonant scatterers. Cavities of mixed sizes and locally resonant scatterers of mixed types can be used to achieve efficient absorption over an ultrawide band. This broadband absorption is found to be attributed to the hybrid-mechanism of the resonances of the cavities and the locally resonant scatterers. Furthermore, the absorption mechanism is illustrated by the displacement patterns, the absorption contribution decomposition analysis, and the effective medium theory.

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I. INTRODUCTION
Waterborne sound absorption structures are often attached to the hull of a submarine for its acoustic camouflage to sonars1 or laid on the backing wall of a sonar dome to reduce the acoustic reverberation effect.2 It is desirable for the absorption structures to absorb the acoustic energy of an incident waterborne sound wave in a wide band as much as possible. A waterborne sound absorption structure is often made of a rubber layer embedded with periodically or randomly distributed inclusions.3–8 Inspired by the sound attenuation effect of bubbles in water, air cavities were introduced into rubber layers for constructing waterborne sound absorption structures during World War II.9,10 Rubber layers with air cavities are often referred to as Alberich-type coatings.11 When the cavities oscillate, the loss of sound waves in rubber is enhanced through the effect of local enlargement of shear strain around the walls of cavities.12 Alberich-type coatings can achieve efficient absorption with a bandwidth of about one octave,13 and the central absorption frequency can be tuned by the cavity size and the elastic parameters of rubber;14 the absorption band of an Alberich-type coating can be broadened using cavities of mixed sizes.15,16 It is challenging to improve low-frequency absorption. If the thickness of the coating is fixed, absorbing lower-frequency sound needs cavities to have a larger size in the layer plane (the plane parallel to the surface of the coating). Enlarging the cavity size in the layer plane can reduce the ability of the coating to operate under high hydrostatic pressures.17

A phononic crystal with locally resonant (LR) scatterers was proposed by Liu et al.18 for implementing bandgaps or transmission dips at frequencies far lower than those of the Bragg phononic crystals. This work has led to an interesting research called acoustic metamaterials19 in the past dozen years which has provided new ideas for elastic and acoustic wave control at low frequencies.20–22 When material loss is considered, strong wave energy absorption can be produced in metamaterials. Chen, Barnhart, and Huang et al.23–25 investigated dissipative elastic metamaterials for broadband wave mitigation, and the wave attenuation mechanism of negative effective mass density and effective metadamping was revealed. Zhao et al.26–28 introduced the locally resonant metastructure to the design of underwater sound absorption materials and found that the resonances of the locally resonant scatterers in a viscoelastic rubber layer can furnish strong absorption of
low-frequency sound waves. A series of work on the design of waterborne sound absorption structures based on locally resonant metamaterials has been published, which focused on broadening the absorption band by changing the structure of the locally resonant scatterers.

In contrast to the above-mentioned studies on the design of waterborne sound absorption structures, which used only one type of resonance structure, cavities, or locally resonant structures, there are significantly fewer studies on the design method of combining different resonance effects. In a recent study, Sharma et al. investigated the sound absorption of rubber coatings with cavities and hard inclusions, but the results did not show broadband absorption performance.

In this paper, a new hybrid-mechanism metastructure combined resonances of locally resonant metastructures and cavities is proposed for achieving broadband waterborne sound absorption. The ability of the locally resonant metastructure to enhance the low-frequency absorption performance is demonstrated. Physical mechanisms associated with the coupling resonances of cavities and locally resonant scatterers are analyzed by the displacement fields, absorption contribution decomposition, and effective medium theory.

II. MODELS AND ABSORPTION CHARACTERISTICS

A. Models

In the proposed hybrid metastructure, a periodic array of locally resonant (LR) scatterers is embedded into the steel-plate backing of a rubber layer with a periodic array of cylindrical cavities. Each LR scatterer consists of a metal core coated by a soft shell made of porous silicone rubber. Two different configurations are considered, and Fig. 1 shows the cross section of a unit cell of the models, model I and model II. The structures are extended infinitely along the axis perpendicular to the plane of the cross section and are covered by half infinite water below and half infinite air above.

A plane-wave sound is incident from the water below. In model I [Fig. 1(a)], there is only one size of cavities and one type of LR scatterers. In each unit cell, there is one cavity in the rubber layer and four LR scatterers in the steel plate. In model II [Fig. 1(b)], cavities of two sizes and LR scatterers of two types (LR scatterer I and LR scatterer II) are introduced. The soft shells of LR scatterer I and LR scatterer II are different, whereas the cores are the same. The dimensions of the models are governed by the steel plate thickness \( h_0 \), the rubber coating thickness \( h_r \), the metal core radius \( a_{i0} \), the soft shell thickness \( t \), and the width of the unit cell \( d \). The radius of the cavity in model I is denoted by \( a_i \), and the radius of the two cavities in model II are denoted by \( a_{i1} \) and \( a_{i2} \), respectively.

B. Absorption characteristics

Studying the sound absorption characteristics of the structures is formulated as a two-dimensional acoustic-solid interaction problem, which can be solved by the finite element method (FEM). The water and air are modeled as acoustic media, with sound pressure governed by the Helmholtz equation. The incident sound with circle frequency \( \omega \) is assumed as \( p_i(x, y) = p_0 \exp\left[i k_w (x \sin \theta_i + y \cos \theta_i)\right] \), where the time harmonic factor \( \exp(-i \omega t) \) is omitted, \( k_w \) is the wavenumber of the water, and \( \theta_i \) is the incident angle. The steel plate and the metal cores are modeled as elastic solid; the rubber matrix and the soft shells are modeled as solid with loss. The displacement fields of solid media are governed by the Navier equation. The reflected sound pressure \( p_r \) in the water and the transmitted sound pressure \( p_t \) in the air can be calculated by a standard FEM procedure that the software COMSOL Multiphysics provides.

The reflected sound pressure \( p_r \) in the water and the transmitted sound pressure \( p_t \) in the air can be calculated by a standard FEM procedure that the software COMSOL Multiphysics provides. The reflection \( R \) and transmission \( T \) are, respectively, defined as the ratios of the reflected and transmitted acoustic power to the incident power,

\[
R = \frac{1}{p_0^2 k_w d \cos \theta_i} \int_{-d/2}^{d/2} \int_{-d/2}^{d/2} \text{Im}\left(p_r \frac{\partial p_r^*}{\partial y}\right)(x, y = 0) \, dx, \\
T = \frac{\rho_w p_0}{\rho_a k_w d \cos \theta_i} \int_{-d/2}^{d/2} \int_{-d/2}^{d/2} \text{Im}\left(p_t \frac{\partial p_t^*}{\partial y}\right)(x, y = h) \, dx,
\]

where * is the conjugate operator, \( \rho_w \) and \( \rho_a \) are the density of the water and air, respectively; \( h = h_0 + h_r \) is the total thickness of the structure, and \( y = 0 \) and \( y = h \) are the surfaces of the rubber coating and the steel plate, respectively. The absorption is \( \alpha = 1 - R - T \), because the impedance of steel is much larger than that of air, the transmission can be ignored and, therefore, the absorption is approximately equal 1 – \( R \), that is, \( \alpha = 1 - R \).

In this study, we assume \( h_0 = 20 \) mm, \( h_r = 10 \) mm, \( a_i = 1.5 \) mm, \( a_{i1} = 5 \) mm, \( t = 2 \) mm, \( d = 64 \) mm, \( a_{i2} = 1.5 \) mm, \( a_{i1} = 2 \) mm, and \( a_{i2} = 2 \) mm. The water has density 1000 kg/m\(^3\) and sound
velocity 1500 m/s. The air has density 1.29 kg/m$^3$ and sound velocity 340 m/s. The steel has density 7890 kg/m$^3$, compressional-wave velocity 5460 m/s, and shear-wave velocity 2620 m/s. The rubber matrix has density 1000 kg/m$^3$, compressional-wave velocity 1500 m/s, and shear-wave velocity 100 m/s with attenuation 25 dB/wavelength. The soft shells are made of porous silicone rubber. For LR scatterer I, the porous silicone rubber has density 969 kg/m$^3$, compressional-wave velocity 75 m/s, and shear-wave velocity 16.6 m/s. For LR scatterer II, the porous silicone rubber has density 1027 kg/m$^3$, compressional-wave velocity 170 m/s, and shear-wave velocity 16.9 m/s. The wave attenuation of the silicone rubber is 8 dB/wavelength.

According to the effective medium theory and measurements of the porous silicone rubber given by Ref. 32, the soft shells of LR scatterer I and LR scatterer II can be furnished from silicone rubber (with density 1040 kg/m$^3$, compressional wave velocity 1100 m/s, and shear-wave velocity 17 m/s) embedded with air bubbles with porosities 0.068 and 0.013, respectively. Here, the material loss of the rubber and silicone rubber is characterized by the wave attenuation ($\alpha$) in dB/wavelength, which is related to the loss angle ($\delta$), in the equation $\alpha = (40\pi \log_{10} e) \tan(\delta/2)$. In general, the wave attenuation is dependent on frequency but assumed to be independent of frequency for simplicity in this study. This simplification is often taken in theoretical studies on acoustic properties of rubberlike materials, such as Refs. 10, 13, and 25. As mentioned above, the value of shear wave attenuation of the rubber is taken 25 dB/wavelength, which was used in Ref. 13, and the value of wave attenuation of the silicone rubber is taken 8 dB/wavelength, which was used in Ref. 25.

The absorption spectrum of model I with LR scatterers I over 10 Hz–10 kHz for normal incident sound ($\theta_i = 0$) is presented in Fig. 2(a) (solid line). Compared with the absorption spectrum of the rubber-coated steel plate without LR scatterers (dashed line), one can see that embedding LR scatterers into the steel plate causes a strong enhancement of absorption in the low-frequency range (below 1.70 kHz), and the absorption in the medium and high frequency range (above 1.70 kHz) is affected slightly. It can be observed that there are two peaks in the absorption spectrum of the rubber-coated plate with LR scatterers, locating at the frequencies near 0.93 kHz and 6.05 kHz.

Figure 2(b) shows the absorption spectrum of the structure in model II for normal incident sound (solid line). Compared with the absorption spectrum of the structure without LR scatterers (dashed line), it can be observed that the rubber layer with cavities of two sizes can furnish an effective absorption in the frequency band above 1.87 kHz, and the absorption at the frequencies below 1.87 kHz is improved by introducing LR scatterers. There are two strong absorption peaks in the low-frequency range. The structure can achieve a wide-band absorption over the frequency range from 0.78 kHz to 10 kHz, measured for the frequency points at which the absorption is larger than 0.75, i.e., the reflected sound pressure is less than half of the incident sound pressure.

Figure 3 presents the incident-angle-dependent absorption spectra of the metastructure in model II. The horizontal and vertical coordinates represent the frequency and the angle of incidence, respectively, and the color represents the absorption coefficients. The result shows that the absorption decreases as the incident angle increases in general, but strong and broadband absorption can be retained over a wide incident angle range from $0^\circ$ to about $45^\circ$ and the frequencies of the two peaks of the absorption spectra in the low-frequency range are almost unchanged with the incident angle.
III. ABSORPTION MECHANISMS

In order to give a deeper understanding of the absorption mechanism, we calculate the absorption contributions of the LR scatterers and the rubber coating with cavities, the displacement patterns, and the effective medium parameters of the structure. For simplicity, only the case of normal incidence is considered in the following analysis.

A. Resonance modes and absorption contribution decomposition analysis

The contribution of each absorption element (the rubber coating with cavities and the LR scatterers) is important for understanding the acoustic behavior of the structure and can be obtained by integrating the power dissipation density on its domain. The absorption of an element \( q = c, LR, LR1, LR2 \) denotes the LR scatterers in model I, the LR scatterers I and LR scatterers II in model II, respectively)

\[
\mathcal{A}_q = \frac{2p_w c_o d}{|p_o|^2} \int_{\Omega_q} \frac{1}{2} \omega \left( \nabla \mathbf{u} \right)^* : \text{Im}(\mathbf{C}) : \nabla \mathbf{u} \, dx \, dy ,
\]

where \( \mathbf{u} \) is the displacement and \( \mathbf{C} \) is the complex elastic tensor.

Figure 4 shows the absorption contribution of the LR scatterers \( \mathcal{A}_{LR} \) (solid line) and rubber coating \( \mathcal{A}_c \) (dashed line). The absorption of LR scatterers has a strong peak near 0.93 kHz and a weak peak near 4.41 kHz. This indicates that the strong absorption of the structure near 0.93 kHz is mainly in the LR scatterers. In the frequency range above 3 kHz, the absorption is mainly produced in the rubber coating. The absorption of the rubber coating is weakened near the absorption peaks of the LR scatterers; thus, the LR scatterers and the cavities are coupled.

Figure 5(a) shows the normalized amplitude of displacement components \( |u_x| \) (perpendicular to the propagation direction) and \( |u_y| \) (parallel to the incident direction) at 0.93 kHz (the first absorption peak of the structure). Due to the symmetry of the structure, only half of the unit cell shows the displacement fields. It can be observed that a large part of the displacement field is localized in the LR scatterers, whereas the steel materials and the rubber coating undergo a weaker movement parallel to the \( y \) direction. The inner metal core of the LR scatterers move as rigid bodies parallel to the \( y \) direction, whereas the outside soft shells undergo a deformation with both components of the displacement. Thus, the first absorption peak (0.93 kHz) of the structure can be understood as the core-resonance mode of the LR scatterers. The metal core and the soft shell act as a mass and a spring with damping, respectively. Figure 5(b) shows the displacement field associated with the second absorption peak of the structure in Fig. 2(a) occurring at 6.05 kHz. We note that the rubber near the cavity wall undergoes a large deformation with both components of the displacement field, whereas the steel plate with LR scatterers is almost at rest, acting as a hard backing. Thus, the second absorption peak (6.05 kHz) of the structure can be understood as the resonance of the cavity. Figure 5(c) shows the displacement field at the frequency of the second peak of the absorption contribution of the LR scatterers \( \mathcal{A}_{LR} \) (4.41 kHz). One can see that both the cavity and the soft shell of the LR scatterer undergo obvious deformation. Thus, the absorption of the structure at 4.41 kHz is derived from the deformation of the cavity walls in rubber coating and the soft shells. The second peak of the \( \mathcal{A}_{LR} \) originates from a localized mode of the soft shells of the LR scatterers.

Figure 6 shows the absorption contributions of the LR scatterers \( \mathcal{A}_{LR1} \) and \( \mathcal{A}_{LR2} \) and cavities \( \mathcal{A}_c \) in model II. It can also be observed that the LR scatterers dominate the absorption in the low-frequency range, whereas the cavities dominate the absorption in the high-frequency range. The LR scatterers with different silicone rubber produce absorption peaks at separated frequencies. The frequency of the first absorption peak of the LR scatterers with soft shells of lower wave velocities (LR scatterer I) is lower than that of the LR scatterers with soft shells of higher wave velocities (LR scatterer II). This indicates that the first and second absorption peaks of the structure in model II are caused by LR scatterer I and LR scatterer II, respectively.

Figure 7 shows the normalized amplitude of displacement of model II at (a) 0.90 kHz (the first absorption peak), (b) 1.54 kHz (the second absorption peak), (c) 4.0 kHz, and (d) 9.0 kHz. It can be observed that the first and second absorption peaks of the structure are caused by the inner core resonances of LR scatterer I and LR scatterer II, respectively. At the beginning of the frequency range in
which the rubber coating dominates the absorption, the larger cavity produces strong vibration and deformation, whereas the smaller cavity is almost at rest. At the higher frequencies, such as 9.0 kHz, the smaller cavity also undergoes strong deformation. Therefore, the cavities of mixed sizes contribute to achieve the broadband absorption in the frequency range above the locally resonance frequencies.

B. Effective medium analysis

According to the Bloch theorem, for the normally incident sound, the reflected and transmitted sound waves can be represented by Fourier series:

\[
\begin{align*}
p_r(x,y) &= \sum_{n=-\infty}^{\infty} [p_n]_0 \exp[i(-k_a y + \alpha_n x)], \\
p_t(x,y) &= \sum_{n=-\infty}^{\infty} [p_n]_0 \exp[i(k_n'(y + h) + \alpha_n x)],
\end{align*}
\]

where \(\alpha_n = \frac{2\pi n}{\lambda_\text{eff}}, k_a = \sqrt{k_n^2 - \alpha_n^2},\) and \(k_n' = \sqrt{k_n^2 - \alpha_n^2}\) (\(k_n\) is the wavenumber in the air). In the low-frequency range \((d < \frac{2\pi}{k_n}),\) only the zero-order components \((n = 0)\) of the reflected and transmitted waves are propagated. Because the zero-order components propagate in the normal direction, the far-field acoustic response of the structure acts like a homogeneous layer. The effective parameters (effective density \(\rho_{\text{eff}}\) and wavenumber \(k_{\text{eff}}\)) of the structure are defined by those of the homogeneous layer, which has the same acoustic response as the structure, and can be retrieved from the scattered waves,

\[
\begin{align*}
k_{\text{eff}} &= \frac{1}{h} \arccos \left( \frac{Z_a(1 - \gamma^2) + Z_w \tau^2}{[Z_w(1 + \gamma) + Z_a(1 - \gamma)]\tau} \right), \\
\rho_{\text{eff}} &= \frac{\frac{1}{2} \int_{-\frac{h}{2}}^{\frac{h}{2}} p_t(x,y = h) dx}{\omega \tau \sin(k_{\text{eff}} h)},
\end{align*}
\]

where \(Z_a\) and \(Z_w\) are the impedances of air and water, respectively, \(\gamma = \frac{[p_1]}{[p_0]},\) and \(\tau = \frac{[p_t]}{[p_0]}\). Note that \([p_1]_0 = \frac{1}{h} \int_{-\frac{h}{2}}^{\frac{h}{2}} p_t(x,y = 0) dx\) and \([p_t]_0 = \frac{1}{2} \int_{-\frac{h}{2}}^{\frac{h}{2}} p_t(x,y = h) dx\). Equation (4) is an extension of the formulas given by Ref. 35 for the case that the structure is placed between two different fluids.

The normalized effective density \(\bar{\rho}_{\text{eff}} = \rho_{\text{eff}}/\rho_{\text{avg}}\) (where \(\rho_{\text{avg}}\) is the average density of the structure) and wavenumber \(k_{\text{eff}}\) below 3 kHz are calculated using Eq. (4) to make a deeper understanding of the absorption mechanism in the low-frequency range. Figure 8 shows the effective density (upper panel) and wavenumber (lower panel) of the structure below 3 kHz for model I. It can be observed that both the imaginary parts of the effective density and wavenumber have a strong peak near the frequency of the first absorption peak of the structure. Thus, the wave propagating parallel to the incident direction attenuates very fast and this attenuation mainly originates from the inertial loss (described by a complex density) of the structure. The inertial loss is caused by the resonance of the inner core of the LR scatterer. The real part of the effective density undergoes a big jump from a large positive value to a small negative value near the resonance frequency. This effect is caused by the relative motion of both the imaginary parts of the effective density and wavenumber. The inertial loss is caused by the resonance of the inner core of the LR scatterer. The real part of the effective density undergoes a big jump from a large positive value to a small negative value near the resonance frequency. This effect is caused by the relative motion of the inner cores of the LR scatterers and the steel matrix of the backing plate and leads to impedance matching of the structure to the water. The input impedance of the structure is \(Z_{\text{in}}\),

\[
Z_{\text{in}} = -iZ_{\text{eff}} \tan(k_{\text{eff}} h),
\]

where \(Z_{\text{eff}} = \omega \rho_{\text{eff}}/k_{\text{eff}}\) is the effective impedance of the structure. The normalized wavenumber \(k_{\text{eff}} h\) represents the ratio of the thickness to the wavelength and is often small in the low frequency range, as shown in Fig. 8 (lower panel). Thus, the input impedance of the structure can be approximated by

\[
Z_{\text{in}} = -i\omega \rho_{\text{eff}} h
\]
in the low frequency range, and the impedance matching condition, which is equivalent to the condition for perfect absorption, can be obtained by

\[ \text{Re}(\rho_{\text{eff}}) = 0, \quad \text{Im}(\rho_{\text{eff}}) = \frac{\rho_0 c_0 \omega}{\rho_0 c_0 \omega} . \] (7)

Equation (7) implies that small real part and the large imaginary part of the effective density lead to strong absorption, and this condition is satisfied near the locally resonance frequency [as shown in Fig. 8 (upper panel)]. Hence, the low-frequency strong absorption of the structure is relevant to the extraordinary property of the density, which is induced by the locally resonance of the metastructure.

Figure 9 shows the effective density (upper panel) and wavenumber (lower panel) of the structure in model II. The resonances of the two different LR scatterers also lead to a strong inertial loss and wave attenuation. Near the inner-core resonance frequencies of the two different LR scatterers, both the imaginary parts of effective density and wavenumber have two strong peaks, and the real part of the effective density experiences a big jump from a large value to a small value. However, the jump of the density at the resonance frequency of the LR scatterers I cannot reach a small value close to zero, which means the impedance matching condition in Eq. (7) cannot be satisfactorily met, and thus, perfect absorption cannot be achieved at this resonance frequency. As shown in Fig. 2(b), the first absorption peak is not close to 1. In comparison, the jump of the density at the resonance frequency of the LR scatterers II can reach a small value close to zero, and thus, perfect absorption cannot be achieved. As shown in Fig. 2(b), the second absorption peak is very close to 1.

IV. CONCLUSION

In summary, we have proposed a hybrid-mechanism metastructure combined resonances of locally resonant metastructure and air cavities for broadband waterborne sound absorption. The ability of locally resonant metastructures to improve the low-frequency sound absorption of the cavity-embedded rubber layer with a steel-plate backing has been demonstrated. Absorption mechanisms have been analyzed by the displacement patterns, the absorption contribution decomposition, and the effective medium theory. The results show that the inner-core resonance trapped mode of the locally resonant scatterer leads to a strong inertial loss, wave attenuation, and impedance matching to the water and thus makes efficient absorption of sound. The combination of the resonances of the locally resonant scatterers in the low-frequency range and the resonances of the cavities in the high-frequency range leads to broadband sound absorption. The resonant frequency of the cavity can be tuned by its size, and the resonant frequency of the locally resonant scatterer can be tuned by the compressibility of the soft shell. Cavities of mixed sizes and locally resonant scatterers of mixed types were designed to achieve low-frequency and ultrabroadband sound absorption. The proposed hybrid-mechanism absorption metastructure provides a new design method for broadband waterborne sound absorption.

ACKNOWLEDGMENTS

This research was supported by the National Natural Science Foundation of China (Grant Nos. 51805537 and 51775549).

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