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REVIEW

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# Recent study progress of underwater sound absorption coating

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**Abstract**

Based on the recent development of underwater sound absorption coatings, this paper analyzes the evolution of underwater sound absorption coatings from two aspects: traditional structures and metamaterials. The traditional structures are divided into three types: cavity structures, composite structures, and impedance-matching structures. First, the development history of traditional structures, from cavities to hybrid structures, is presented, and the optimization and recent improvements in sound absorption fundamentals are explained. For different types of structures, the sound absorption effects of their respective structures are presented. At the same time, recent development progress of underwater coating metamaterials is summarized, and the sound absorption fundamentals and effects of local and nonlocal resonance types are compared. In addition, typical underwater sound absorption metamaterials are described in detail, and the application prospect of the acoustic bubble structure in practice is summarized. Moreover, this paper compares and discusses various structural types of underwater sound absorption coatings and points out the shortcomings of recent related research. Finally, it points out current open issues in the field and suggests future development directions of underwater sound absorption coatings, defining the possible development focus of underwater sound absorption coatings.

**KEYWORDS**

bubble, cavity structure, composite structure, metamaterial, underwater sound absorption

## 1 | INTRODUCTION

Submarines play a crucial role in sea power maintenance in many countries. To improve their viability, the main way has been to reduce the acoustic target strength by laying a sound absorption coating on the shell. The purpose of laying sound absorption coating[1] is twofold. First, it reduces the radiated noise level, thus reducing the probability of being detected by enemy passive sonar and its operating range. Second, it reduces the intensity of the acoustic target, thus increasing the detection range of the enemy's active sonar.

The earliest underwater sound absorption coating could be traced back to the end of World War II, when the German navy began to install a coating of synthetic rubber sound-proof material[2] named "Alberich anechoic coatings" on the

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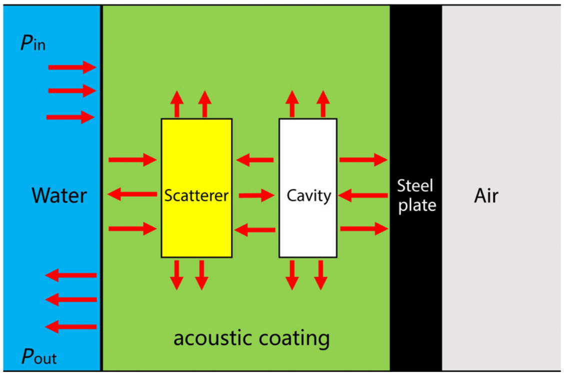

FIGURE 1 Schematic diagram of the sound absorption mechanism of sound absorption coating

shell of submarines, with a thickness of about 30 mm and a cylindrical cavity with an inner diameter of 2–5 mm. This layer could absorb the sound energy by using the bubble deformation generated when sound was incident and played a certain role in reducing reflection and noise. In addition, this "Ali Berich" synthetic rubber sound-proof material could be considered the first sound absorption coating used in practice in the world. In widely used acoustic stealth equipment, underwater sound absorption coating can absorb acoustic waves emitted by active sonar, inhibit hull vibrations, and isolate the noise inside a ship. Therefore, the sound absorption coating has become the key submarine component that can effectively counter an enemy's active sonar and realize passive sonar detection.

As shown in Figure 1, the sound absorption mechanism of sound absorption coating can be roughly divided into three stages: (1) sound waves enter the coating from the water, (2) sound waves propagate in the coating, and (3) sound energy is dissipated in the coating.

In the water, the incident sound wave enters the covering material through the intermediate water medium. In the acoustic wave incident interface, the material that has the most similar characteristic impedance to that of the incident medium water medium is selected as an outer surface material of the coating to achieve impedance matching. Thus, when the acoustic wave is incident from the water to the coating surface, due to the impedance matching, the incident acoustic wave can enter the coating to the maximum extent, and the reflected wave can be maximally reduced.

When an underwater acoustic wave enters the overburden, it is dominated by a longitudinal wave. Because the shear loss factor of the sound absorption coating is much higher than that of the longitudinal wave, the shear wave attenuation is larger, which can increase the energy loss significantly. In addition, at the rubber–water interface, the shear wave is difficult to refract from the rubber body to the water, so it is required to increase the longitudinal wave conversion in the covering coating to the shear wave. Due to the mismatch in the acoustic impedance between the coating and the steel plate, the generated shear wave cannot be completely transmitted to the water, and multiple reflections will occur on the upper and lower surfaces of the coating. However, by adding cavities and inclusions in the coating, sound waves will be scattered when encountering.

The existence of cavities and inclusions can make a plane longitudinal wave continuously transform into a shear wave when propagating in the sound absorption coating, thus improving the waveform transformation process. In addition, scatterers change the acoustic wave propagation direction from longitudinal to oblique or even radial, increasing their propagation path in the anechoic tile so that the acoustic reflected wave is scattered at multiple angles in the coating. Generally, the higher the frequency of a sound wave is, the higher the efficiency of the wave mode conversion will be. Therefore, waveforms in the middle and high-frequency bands of a sound absorption coating structure play a significant role.

Currently, sound absorption has been mainly achieved through internal loss and cavity resonance. Most sound absorption materials represent viscoelastic media, and due to the viscous resistance characteristics of viscoelastic materials, when deformation occurs under the action of sound waves, part of the sound energy will be converted into heat energy, and the remaining part will be dissipated through the friction and elastic relaxation process inside the materials. In addition, the sound wave generates local resonance near the cavity and inclusion, and large deformation displacement is generated in the sound absorption material. This enhances the internal friction and elastic relaxation process of material so that its absorption performance of sound waves is greatly increased, and the periodically arranged scatterers can generate excessive sound absorption.

The traditional sound absorption coating generally has a cavity structure and uses composite materials doped with particles, where the sound wave propagation is very complex. At present, the frequency range of sound absorption coating structure research has been from the low-frequency band where the sound wave wavelength is approximately equal to the structure size. The energy conversion forms include direct conversion of sound energy to heat energy, conversion of sound energy to kinetic energy and then to heat energy, and conversion of sound energy to electric energy and then to heat energy. Further, the sound absorption mechanism includes many absorption types, such as viscoelastic loss absorption, periodic scattering absorption, wave-type conversion absorption, low-frequency resonance absorption, and piezoelectric absorption. The existing sound absorption coating structures include gradual impedance sound absorption structures, sandwich composite sound absorption structures, particle composite sound absorption structures, pressure-resistant composite sound absorption structures, acoustic crystals, cavity resonant sound absorption structures, micro-perforated sound-absorption structures, and piezoelectric composite sound absorption structure.

An acoustical metamaterial is a type of periodic or aperiodic structure that can achieve extraordinary acoustic or mechanical properties that conventional materials do not have through the orderly design of some structures on the sub-wavelength dimension (i.e., one-tenth of the wavelength). The development of acoustic metamaterials started from the study of locally resonant phononic crystals. Liu et al.[3] proposed a phononic crystal by analogy with photonic crystals, whose lattice constant is two orders of magnitude smaller than the acoustic wave wavelength. The phononic crystal is a composite material of local resonant structural units, which can show effective negative elastic constants in a certain frequency range and generate a low-frequency elastic-wave band gap. Since then, much exploration work on the acoustic metamaterial application in the fields of vibration reduction and noise reduction has been done, mainly considering the air acoustic metamaterials[3-17] and underwater acoustic metamaterials.[18-41] However, this study describes only the local and nonlocal resonance underwater acoustic absorption metamaterials, considering the sound absorption coating of metamaterials.

In this paper, the research status of traditional and metamaterial-based sound absorption coatings is analyzed from the aspect of the sound absorption performance of sound absorption coatings, and the acoustic stealth technology of coating materials is prospected.

## 2 | TRADITIONAL STRUCTURE

The early use of sound absorption coatings can be traced back to World War II, when this coating was used to reduce the noise of submarines and prevent them from being detected. The rubber coating has been commonly used as an accessory of underwater structures[2] to reduce the reflection of incoming sound waves. The traditional sound absorption coating structures mainly include cavities in addition to the composite and impedance-matching structures. The division of sound coating mainly composed of traditional structures is shown in Table 1.

TABLE 1 Division of sound absorption coating of traditional structures

| | | |
|---|---|---|
| Type with cavity | With cavities of different shapes | The sound absorption effect is achieved through the resonance of the cavity, and the internal friction and elastic relaxation process of the material are enhanced. |
| | With periodic gratings | Use the scattering effect of periodic grid on plane acoustic wave to achieve sound absorption effect. |
| Containing hybrid structure | Containing micro inclusions | It is embedded in various media to produce multiple scattering effects and achieve sound absorption. |
| | Containing micropores | The absorption in the low frequency range can be significantly enhanced by using pore absorption |
| Impedance matching structure | It can improve the impedance matching characteristics between the sound absorber and the fluid medium, and improve the sound absorption capacity. Different material layouts will produce different sound absorption effects. | |

## 2.1 | Structure with cavity

### 2.1.1 | Different cavity types

Inspired by the sound attenuation effect of bubbles in the water, relevant studies have introduced cavities into rubber coatings to design underwater sound absorption structures. As mentioned before, during World War II, Germany applied a rubber coating with a cavity,[42] which has been called the Albertich-type coating. When the cavity oscillates, the acoustic loss in the rubber will be enhanced due to the local increase in the shear strain around the cavity wall, thus achieving the sound absorption effect. The analysis of sound absorption coating containing periodic cavities originated from the work of Meyer et al. Gaunaurd[43,44] proposed a one-dimensional analysis method for viscoelastic media containing short cylindrical cavities. It was demonstrated that the rubber coating, including cavities, could significantly reduce the underwater reflection of steel plates to sound energy, and the resonance modes of cavities with different physical sizes were explained.

For different cavity shapes, such as sphere,[45,46] ellipsoid,[47,48] cylinder,[49] and disk,[50] their acoustic performances have been studied, and effective sound absorption coatings were developed for noise control. The diagram of the relevant cavity structure types is presented in Figure 2.

Subsequent studies used the shear wave characteristics of rubber materials to design various types of rubber coatings. Ivansson[52] studied the sound absorption performance of viscoelastic coating for periodically distributed cavities. He derived the relationship between the viscoelastic loss in the rubber coating and the monopole resonance scattering loss of isolated cavities and concluded that when a spherical cavity was introduced, the shear wave parameters of rubber could be appropriately specified, and the rubber coating with a thickness of 6% of the longitudinal wave wavelength (far less than a quarter of the wavelength) could eliminate reflection.

To improve the low-frequency performance of composite sound absorption coating, Tao and Xing[53] embedded additional viscoelastic material into the viscoelastic matrix of the traditional sound absorption coating to realize a composite sound absorption coating. The numerical results showed that with the increase in the embedded coating proportion, the peak frequency of the sound absorption coefficient moved to lower values, and the low-frequency sound absorption performance was improved. Later, Tao[51] designed a simplified prediction model of the acoustic

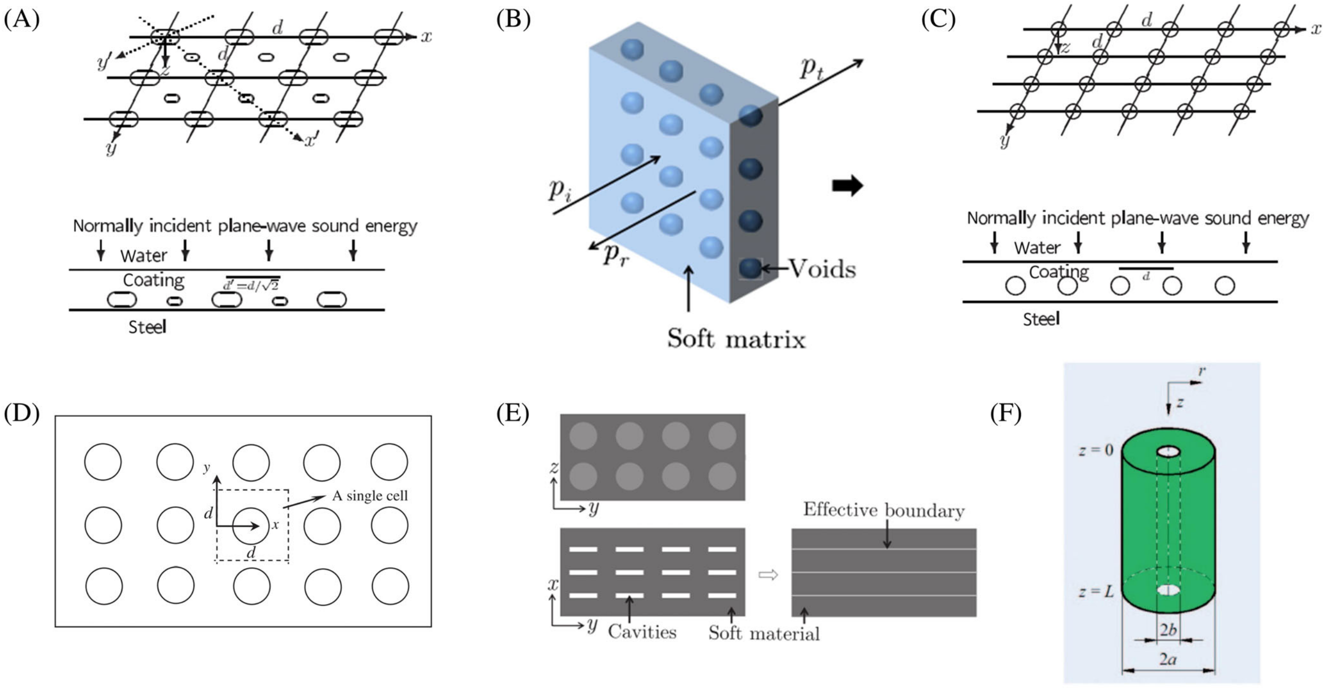

**FIGURE 2** (A) The periodic arrangement of ellipsoids and spherical cavities[46]; (B)–(D) arrangement of spherical cavities[45,46,49]; (E) the overall coating structure[50]; (F) cylindrical cavity structure[51]

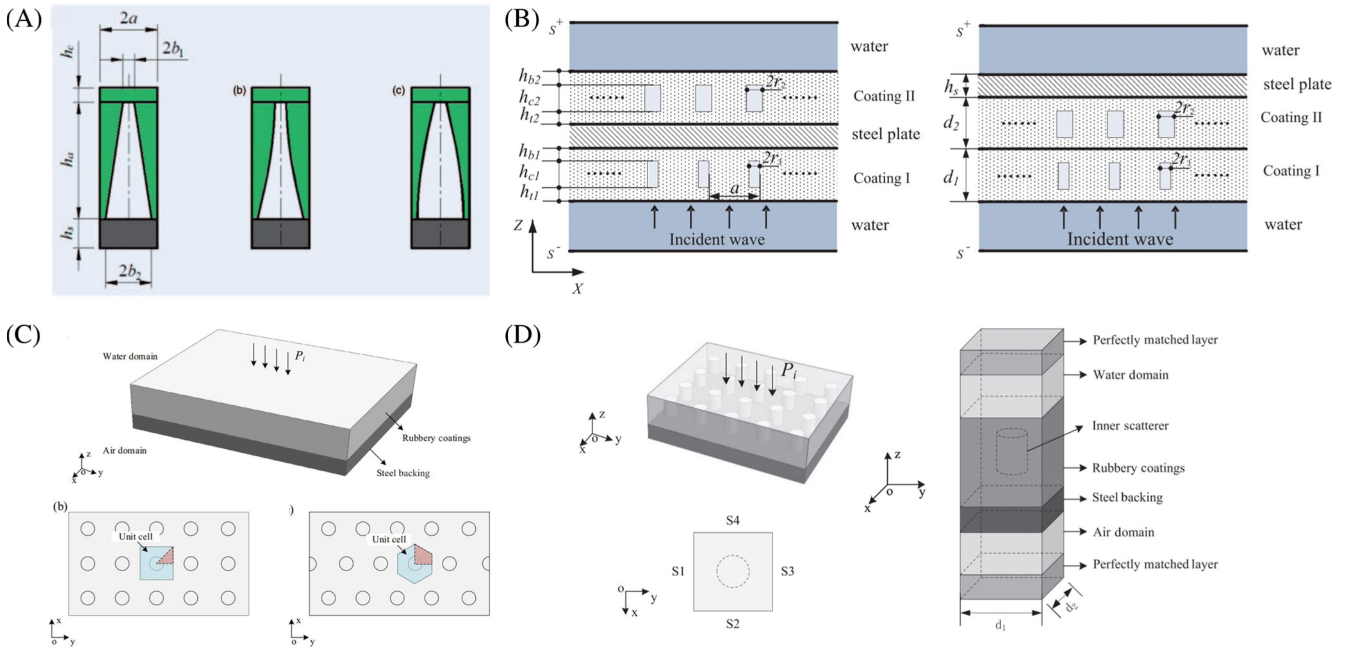

**FIGURE 3** (A) Schematic diagram of a cavity structure of the cylindrical, tapered, and horn-shaped holes;[51] (B) cylindrical cavity profile[54]; (C) schematic diagram of square and hexagonal cavity arrangement[55]; (D) nonuniform sound absorption coating structure embedded in cavity[56]

performance of the underwater sound absorption coating and established a simplified analytical model of the underwater sound absorption coating with hexagonal arranged deformed cylindrical cavities, as shown in Figure 3A. It was concluded that the low-frequency acoustic performance of the sound absorption coating was defined by the propagation characteristics of the first axisymmetric wave. Finally, the acoustic performance of the sound absorption coating attached to two typical acoustic terminals was discussed; one terminal was the sound absorption coating steel plate arrangement, and the other was the sound absorption coating—front steel plate—reclaimed water—rear steel plate arrangement.

Fu et al.[57] studied the sound absorption performance of the anechoic coating embedded in a periodic double cavity and backed with periodic ribs and stiffening plates. The results showed that the plates and ribs had a significant impact on the absorption performance of the anechoic coating, especially at low frequencies. Ye et al.[58] constructed a theoretical model to evaluate the sound absorption performance of underwater anechoic coating with periodically distributed axial holes. Based on the concept of equivalent homogenized coating and the theory of wave propagation in a viscoelastic cylindrical tube, the absorption coefficient of anechoic coating on a viscoelastic cylindrical tube was calculated using a transfer function method. Three different types of axial holes were considered: cylindrical holes, tapered holes, and flared holes. The results of the full finite element simulation were used to verify the model prediction performance. The results showed that the absorption coefficient curve moved toward the low-frequency direction with the hole size. When the hole size was fixed, the horn hole had the best sound absorption performance at a relatively low frequency. Zhao et al.[54] optimized the sound absorption performance of two types of Alberrich coatings on steel plates immersed in water. The specific structure is shown in Figure 4B. It was proved that different sound absorption coatings could achieve a good sound absorption effect in the range of 1.3–10.0 kHz. The results indicated that using different coatings on the steel plate surface could effectively improve the sound absorption performance in the low-frequency bandwidth. Gaunaurd et al.[61] have studied the influence of hydrostatic pressure on the air-filled layer through experiments. However, in recent years, the hydrostatic pressure test for the sound-absorbing coating has still lacked effective verification.

Zhao et al.[55] discussed the accuracy of the axisymmetric simplified model by simulating the cell as a circular cross-section at the optimal sound absorption of 1–20 kHz, as shown in Figure 4C. In addition to the cavity role, recent studies have aimed to change relevant materials and structures to improve the sacrificial effect of the cavity. Calvo et al.[62]

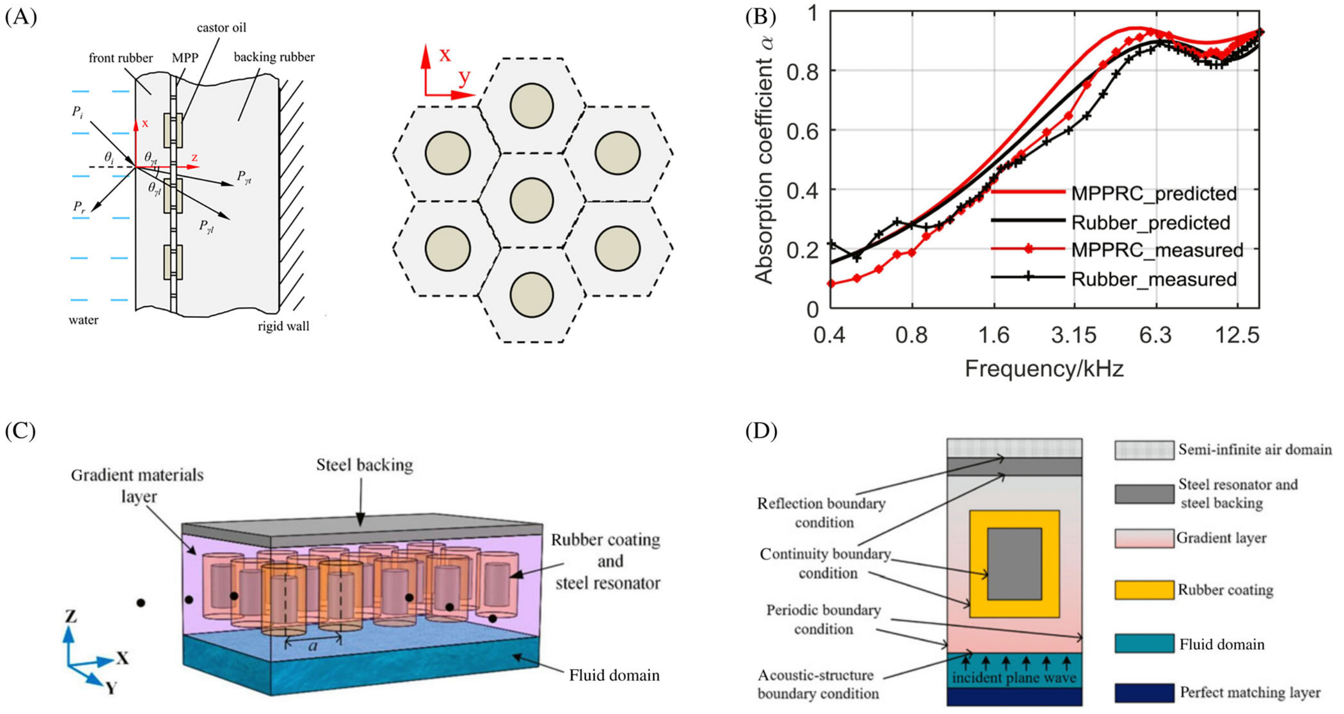

**FIGURE 4** (A) Sound absorption coating structure with a micro-perforated plate;[59] (B) sound absorption coefficient with the micro-perforated plate structure;[59] (C) General view of underwater anechoic coating;[60] (D) local resonator structure embedded with a functionally graded material[60]

micro-machined the discoid cavity array into mono- and multi-coating polydimethylsiloxane and obtained an 18-dB simulated transmission loss at a wavelength of approximately 20 times the thickness of the three coatings. The research of Zhong et al.[56] has shown that, within the relevant frequency range, a small Poisson loss factor has a significant impact on the sound absorption of uniform coatings, while it had a frequency and structure-dependent impact on the sound absorption of non-uniform coatings embedded in cavities. The schematic diagram of the cavity structure is shown in Figure 4D. For given material parameters and cavity size, more obvious effects can be observed for rubber coatings with large lattice constants and thick coatings. Wang et al.[63] studied the sound absorption effect of periodic cavities with the radius and spacing gradient changes in soft elastic media and proved that the structure had a very high sound absorption peak in the frequency range of 600–1400 Hz.

### 2.1.2 | Periodic grids

The formation of grids through periodic cavities plays an important role in the scattering and radiation of sound waves and has an effective sound absorption effect. Yang[64] proposed a new hybrid mechanism substructure, which combines the resonance of the local resonant scatterer with that of the air chamber, and has been used for broadband aqueous sound absorption, significantly improving the sound absorption performance in the low-frequency range. Anne Christian et al.[65] used the finite element method to analyze the scattering of plane acoustic waves from a double periodic structure and proved the accuracy of the finite element method in grid simulation. Hladky-Hennion[66] also used the finite element method to model single- and double-period structures, described specific theoretical development required for two-dimensional structures with one-dimensional periodicity, and suggested that it could be extended to the grid application simulation. Gyani Shankar Sharma et al.[67] analyzed the acoustic performance of cylindrical void grids in soft elastic media under the steel backing condition. They proposed an approximate analysis model and studied the sound transmission, reflection, and absorption of rubber-like media on a steel backing. Sven M. Ivansson[68] studied the rubber coating of a three-dimensional (3D) cavity containing double periodic diffraction grids and compared the frequency response results of grids formed by spherical and cylinder structures.

## 2.2 | Hybrid structure

Composite materials have been commonly used in underwater sound absorption coatings, and they are usually composed of elastic materials based on natural rubber or polyurethane and may include micro-inclusions or micropores to form hybrid structures to adjust the effective sound velocity in a particular medium.

### 2.2.1 | Micro-inclusions

Adding a sound absorption coating composed of cavities, metal balls, and other particles[69-71] to viscoelastic materials such as rubber can generate the multiscattering effect. These effects can enhance the scattering of sound waves in the sound absorption coating at the resonance scattering frequency band of particles. Scattered waves are largely dissipated due to the influence of matrix damping, thus improving the sound absorption performance of the sound absorption coating in this frequency band significantly. Cikai Lin[72] gave the vibroacoustic response of a structural cylindrical shell immersed in water by embedding a circular array of resonant inclusions in a viscoelastic material. He analyzed the influence of inclusion materials, local resonance tuning of inclusions, and the distribution of uniform coatings in the coating on the vibroacoustic response of the shell. Alex Skvortsov[73] proposed a theoretical framework for sound wave propagation in a subsurface composed of hexagonal hard spherical inclusion lattices embedded in soft elastic media and analyzed the sound absorption effect of the structure, considering the multi-scattering effect. Gyani Shankar Sharma et al.[74] studied the sound absorption performance of a rubber medium with periodic hard inclusions, deduced the analytical expressions of damping and dipole resonance frequency of solid cylindrical phonon array in viscoelastic medium, and verified the feasibility of using this medium as the sound absorption coating outside ocean ships.

### 2.2.2 | Microporosity

Gyani Shankar Sharma et al.[75] studied sound transmission in soft elastic media with periodic pores under water and defined the influence of strong and weak resonant coupling of pores on the transmission characteristics. Later, Gyani Shankar Sharma et al.[76] embedded a circumferential coating with equidistant gaps in the soft elastic sound absorption coating with cavities, demonstrating that the radiated sound could be reduced in a wide frequency range after the coating design was adjusted. Gyani Shankar Sharma et al.[77] studied the acoustic performance of viscoelastic media with periodic pores and uncertain parameters, indicating that the uncertainty of geometric parameters had a larger impact on the resonant frequency of cavities and sound transmission through the coating. Sharma et al.[78] analyzed the sound absorption performance of underwater viscoelastic coating composed of periodically distributed pores and hard inclusions. The analysis results have shown that the rubber coating consisting of a coating of hard inclusions and a coating of smaller pore inclusions has a very high sound absorption performance in a wide frequency range.

Apart from the periodic voids, a micro-perforated plate structure can also be added to the structure to improve the low-frequency sound absorption effect of the coating. Li and Zhang[59] proposed a new underwater sound absorption structure based on the microperforated plate (MPP) and viscoelastic substrate, as shown in Figure 4A,B. In the frequency range of 1–15 kHz, the absorption coefficient was significantly improved due to the MPP role. In addition, it was demonstrated that compared with rubber with the same thickness, the sound absorption coating structure with micro-perforated plates could significantly improve the absorption performance.

In addition, Ke et al.[79] proposed an underwater absorber with good low-frequency sound absorption performance, broadband sound absorption performance, and deformation resistance, which is composed of micro-perforated plates, foldable channels, and rubber coating. They designed the underwater substructure with a low-frequency broadband sound absorption performance by optimizing the main parameters of the absorber. Further, Zhang and Pan[80] studied the scattering and absorption of an underwater incident sound using an infinite plate with a coating with uneven distribution, and the results demonstrated that this structure could significantly affect local sound absorption and reflection performances.

## 2.3 | Impedance matching type

The sound attenuation coating with a good sound absorption performance should not only meet the requirements for good impedance matching characteristics of sound structure and fluid medium but also ensure that the acoustic energy entering the sound absorption structure is dissipated maximally. However, no matter how strong the sound absorption capacity of a particular material is, if a sound wave is significantly reflected on the fluid–structure interface, the sound absorption performance of anechoic coating will be very poor. Therefore, improving the impedance matching between an absorber and a fluid medium is essential to improve the sound absorption capacity, and the proposal for an impedance-matching structure has received extensive attention in recent years.

Easwaran and Munjal[81] combined the waveguide theory with impedance matching in the fluid to simulate the reflection characteristics of a resonant absorber under the action of normal incident plane waves and analyzed the sound absorption characteristics of the resonant absorber using the finite element method. Li and Li[82] proposed a method to determine the optimal material layout directly, which significantly improved the absorption performance of the anechoic coating. For the low-frequency numerical case, not only the final material distribution with high absorption performance was given, but also the sensitivity information of the reflection coefficient under a given incident wave was compared. Jia et al.[60] proposed a structure of embedding local resonators in functionally graded materials, which can improve and obtain broadband sound absorption performance at low frequencies, as shown in Figure 4C,D. Feng et al.[83] proposed composite structures with different gradient impedances. The effects of the impedance gradient forms and discrete delamination methods on acoustic performance were studied numerically and experimentally. Laetitia Roux et al.[84] verified the effective properties of composite materials and their acoustic properties through experiments.

The aforementioned works provided useful information on the preparation and testing of large samples in an anechoic tank, but there have still been certain deficiencies in the research related to the sound absorption coating.

# 3 | UNDERWATER ACOUSTIC METAMATERIAL

Liu et al.[3] introduced the idea of local resonance into the design of acoustic materials, air acoustic metamaterials have made great progress because of their excellent low frequency sound absorption properties. A large number of researchers have been interested in the membrane resonators,[4-7] space-coiled channels,[8-11] Helmholtz resonators,[12-17] and so on. With the development of acoustic metamaterials during the last 20 years, significant progress has been made in the research of acoustic metamaterial application to underwater sound absorption. In the following, a detailed introduction to local and nonlocal resonance underwater acoustic metamaterials is provided.

## 3.1 | Local resonance mode

### 3.1.1 | Single-oscillator local resonance

Wen et al.[18,19] proposed using a local resonance element in underwater sound absorption and designed a viscoelastic polymer plate structure with local resonance scatterers embedded uniformly, as shown in Figure 5A. The dynamic mode and sound absorption performance of this structure were analyzed and calculated. The results showed that there were two sound absorption peaks at 870 and 2310 Hz, as shown in Figure 5B. The mode conversion efficiency of a longitudinal wave to the transverse wave at the second sound absorption peak was higher than that at the first sound absorption peak. In addition, the influence of scatterers of different shapes and the eccentricity of scatterers on sound absorption performance were explored, as shown in Figure 5C. It was shown that the two absorption peaks could be easily moved to the low-frequency band using cylindrical scatterers with a small bottom circle radius. Further, the results showed that with the increase in eccentricity, the frequency band below 1500 Hz was almost not affected, while the sound absorption effect was obviously improved above 1500 Hz. To enhance the sound absorption capacity of underwater sound absorption materials at low frequencies further, Gao and Lu[20] proposed an underwater sound absorption material composed of viscoelastic rubber, a conical cavity, and a metal vibrator, as shown in Figure 5D, which shows excellent sound absorption properties in the range of 0–10 kHz. It was explained that the sound absorption mechanism behind the conical cavity rubber composites with a metal vibrator was mainly caused by the waveform conversion. The sound absorption efficiency of the conical cavity with a metal oscillator, the conical cavity, and the homogeneous viscoelastic rubber material were

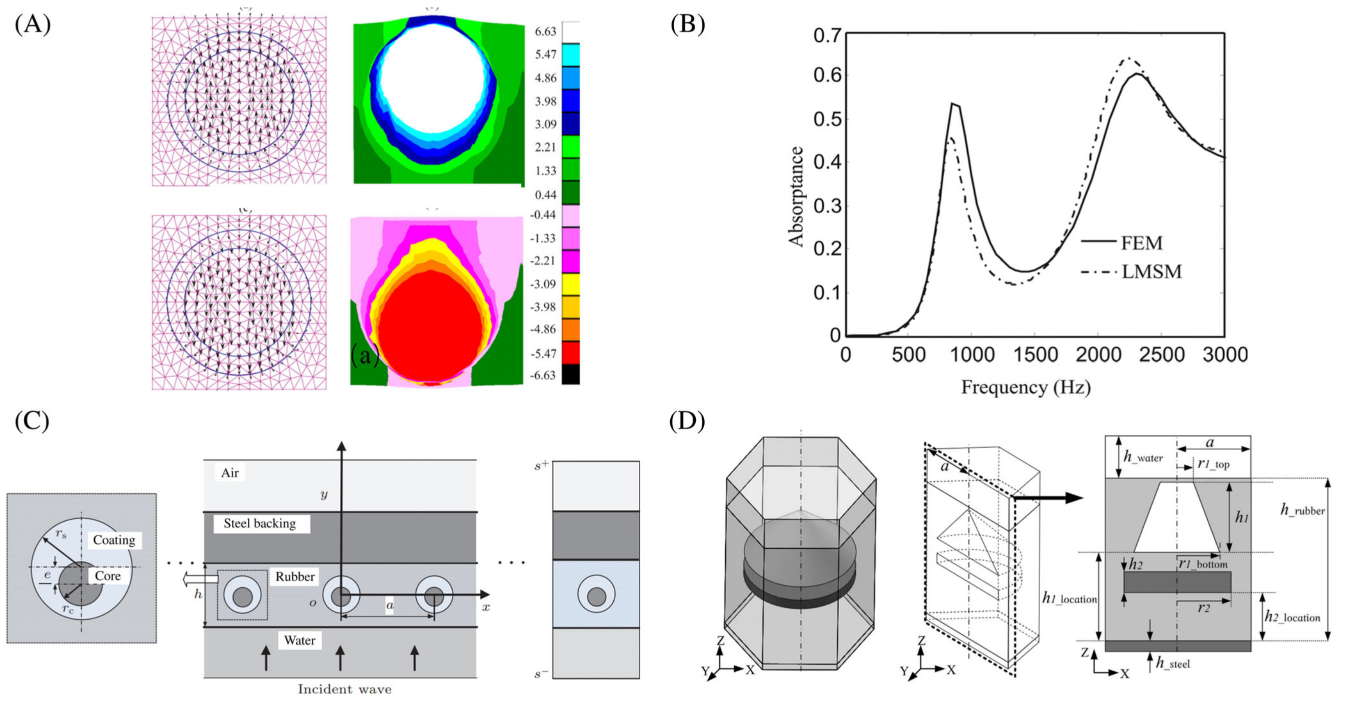

**FIGURE 5** (A,B) Displacement diagrams of the scatterers in the viscoelastic plate embedded with local resonance scatterers near the resonance frequency and their sound absorption properties of underwater sound waves;[18] (C) schematic diagrams of the scatterers under the condition of eccentricity[19]; (D) schematic diagrams of underwater sound absorption metamaterials with metal vibrators and conical cavities[20]

compared. The results indicated that the metal vibrator could enhance the sound absorption ability of the material at low frequencies, and when the backing thickness increased, the experimental results were closer to the simulated finite element results.

In addition, the acoustic metamaterial[21-25] based on the bubble resonance mechanism has also attacked the wide interest of researchers in recent years. Leroy et al.[21] soaked the soft elastic matrix in water to construct a deep subwavelength single-layer bubble-type local acoustic metamaterial, as shown in Figure 6A. Through theoretical calculation, it was found that the material had perfect sound absorption ability in a wide frequency range. Moreover, they considered the strong coupling between bubble resonances fully, which has often been ignored in the research on metamaterials. Cai et al.[22] designed a low-frequency broadband bubble acoustic metamaterial based on 3D printing technology and surface hydrophobicity, as shown in Figure 6B. The structural band gap was analyzed and calculated, and the results showed that the band gap range could reach a value of 2–26 kHz, as shown in Figure 6C. Further, the influence of geometric parameters and solid Young's modulus on the band gap was discussed. It was found that the bubble band gap rate increased with the bubble volume fraction, and using high solid Young's modulus materials could provide an extremely wide band gap. Furthermore, a water–air transmission super surface based on a bubble structure was proposed, as shown in Figure 6D. This structure could provide a new way for underwater acoustic detection and water–air communication.

### 3.1.2 | Multi-oscillator strong coupling resonance

The absorption of underwater sound waves was realized by using the local resonance characteristics of a single oscillator, which had a narrow absorption bandwidth and a low absorption peak. Jiang et al.[26] further broadened the sound absorption frequency band by introducing multiple vibrators into the unit cell structure to realize strong coupling between vibrators to obtain a new resonance form, based on which a type of phonon wooden pile similar to building blocks was prepared. As shown in Figure 7A, each layer of this structure was composed of three steel bars covered with a soft rubber medium, and there was a vertical intersection between the layers. Due to the strong coupling between the vibrators, the band gap of the structure was opened, which provided the broadband absorption of underwater acoustic waves. In

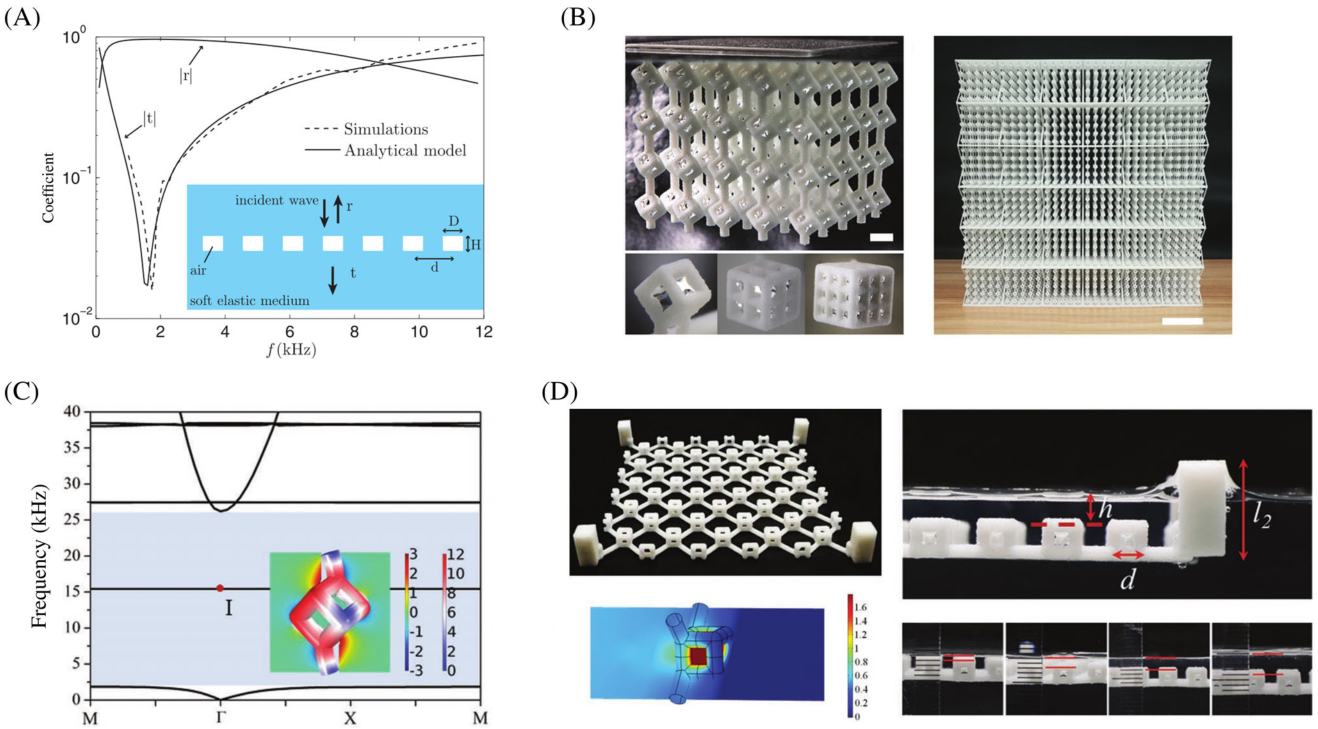

**FIGURE 6** (A) Structure and transmission coefficient diagram of a deep subwavelength single-coating bubble-type local acoustic metamaterial;[21] (B) three-dimensional printing structure of the low-frequency broadband bubble acoustic metamaterial;[22] (C) dispersion curve of the structure presented in (B);[22] (D) schematic diagram of a three-dimensional printing structure, sound pressure distribution, and illustration of a structure floating in the water on the water–air transmission super surface based on the bubble structure[22]

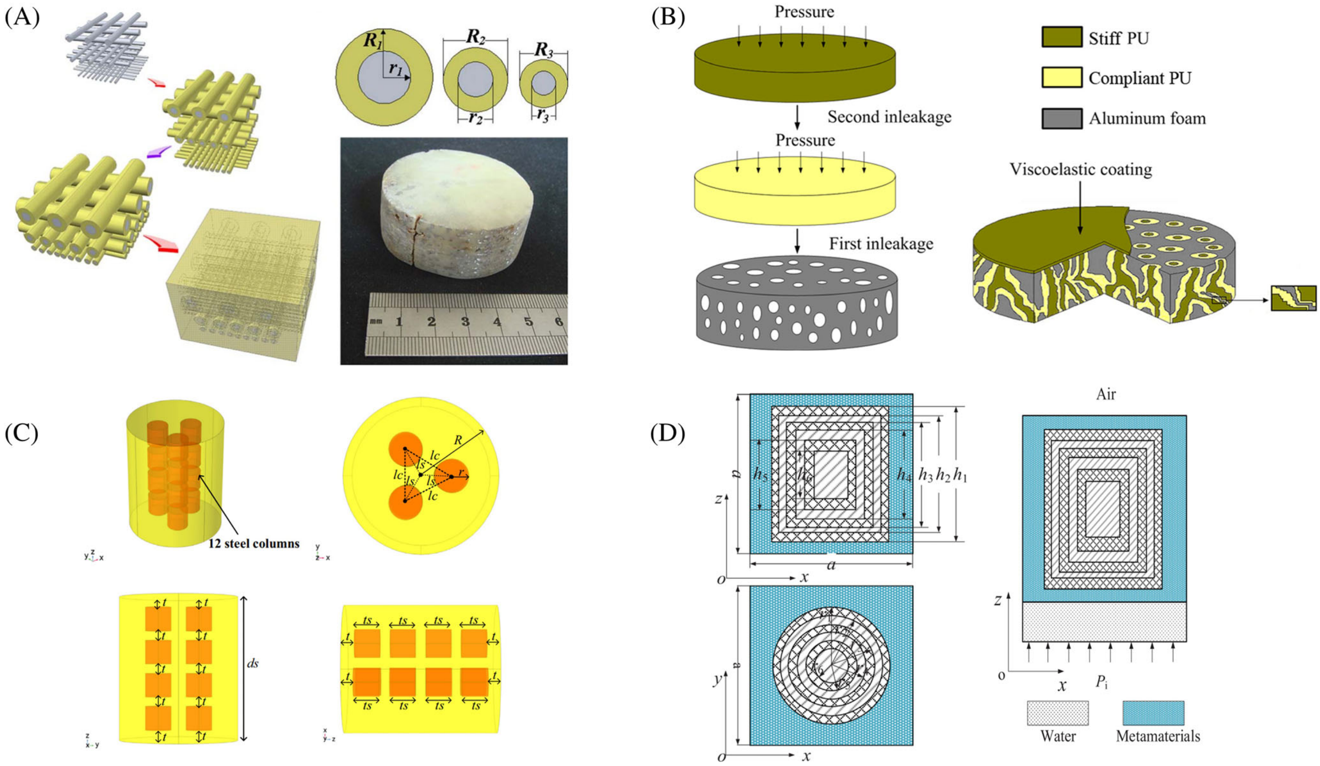

**FIGURE 7** (A) Schematic diagram of a phonon wooden pile and experimental sample diagram;[26] (B) phonon glass structure model;[27] (C) underwater acoustic metamaterial with 12 cylindrical harmonic oscillators;[28] (D) acoustic metamaterial with multicoating local resonance elements[29]

addition, Jiang et al.[27] prepared a phonon glass with local resonance elements added to the composite based on the interpenetrating network structure. As shown in Figure 7B, the sound absorption performance was achieved in the range of 19–30 kHz when the sound absorption coefficient was higher than 0.9. Gu et al.[28] designed an underwater acoustic metamaterial with an efficient, broadband, and low-frequency sound absorption performance in the range from 200 Hz to 2 kHz under high static pressure. As shown in Figure 7C, this structure consisted of 12 cylindrical harmonic oscillators arranged in a rubber matrix material according to certain rules. The sound absorption mechanism behind this type of acoustic metamaterial was to dissipate more sound energy through the strong coupling and multiscattering effect between multiple vibrators. It is worth noting that they also analyzed the change in the sound absorption coefficient of acoustic metamaterials for different resonator structures under the condition of high static pressure. The results showed that the sound absorption coefficient could reach a value of 0.78 in the range of 600 Hz to 2 kHz under the condition of 0.5 Mp. Shi et al.[29] proposed an acoustic metamaterial, which could be used to obtain multilayer local resonance units to further broaden the sound absorption band. As shown in Figure 7D, the analysis of the band gap characteristics of the structure showed that there were multiple band gaps due to the coupling vibration of the multi-layer local resonance unit. Compared with the single local resonance unit, the sound absorption performance of this structure was improved significantly. They also studied the effects of matrix structure parameters, layer thickness, local resonance elements, and matrix materials on sound absorption capacity.

To achieve a highly efficient sound absorption effect in a wide low-frequency band, Zhang and Cheng[30] designed an ultra-thin underwater acoustic metamaterial, where a thin circular plate with a varying thickness gradient was uniformly inserted into the elastomer matrix. As shown in Figure 8A, numerical simulation and experimental tests were performed on the proposed structure, and the results indicated that adding several thin metal plates could improve the resonance morphology of the structure significantly; also, the gradient change in the metal thin-plate structure greatly promoted the coupling resonance modes between the harmonic oscillators. Moreover, the results demonstrated that the average sound absorption coefficient of the ultra-thin underwater sound absorption structure was higher than 0.90 in the frequency range of 500 Hz-2 kHz, as shown in Figure 8B. Furthermore, the influence of the metal round sheet thickness, the loss factor, and the backing thickness on the sound absorption coefficient was examined. It was found that the average sound absorption coefficient increased, and the sound absorption bandwidth became narrow with the metal round sheet thickness in a certain range, which was due to the increase in the thickness and the obvious narrowing of the sound absorption bandwidth with the increase in the rubber matrix loss factor. After the introduction of backing, with the increase in backing, the overall average sound absorption coefficient first increased and then decreased. This was because when the backing increased from zero, at an appropriate thickness, resonance and structure coupling resonance of the backing increased, making the backing thickness further increase from the appropriate thickness, and the contribution of the resonance and structure coupling co-vibration of the backing to the overall capacity decreased. Zhang et al.[31] designed an underwater sound-absorption acoustic metamaterial based on viscoelastic rubber, which included five groups of conical and cylindrical cavities, two metal vibrators, and a rigid backing. It should be noted that the average sound absorption coefficient of this structure could be more than 0.7 in the range of 42–300 Hz, and the sound absorption coefficient of the sound absorption bandwidth could be more than 0.9 in the range of 110–300 Hz. The results showed that the structure had outstanding sound absorption ability due to local resonance, waveform conversion, and multiscattering contribution. Jin et al.[32] proposed a viscoelastic composite underwater sound absorption structure composed of multiple vibrators and cavities. As shown in Figure 8C,D, because of the local resonance of the oscillator, a new resonance was caused by strong coupling excitation between oscillators, cavity resonance, and multiscattering mechanism; also, the sound absorption bandwidth of composite underwater acoustic metamaterials was effectively expanded.

## 3.2 | Nonlocal resonance mode

### 3.2.1 | Acoustic hypersurface

Acoustic hypersurface[33] represents a new type of artificial acoustic structure that can flexibly adjust and control sound waves through phase mutation of the incident and refracted surfaces at a subwavelength scale. Currently, there have been many studies on airborne sound direction but fewer studies on underwater sound control. Mei et al.[34] designed an underwater acoustic wave-absorbing hypersurface structure using water and rubber. They also calculated the material and geometric parameters of the hypersurface using the effective medium theory and iterated. The results showed that the structure was 0.15 times the wavelength. The results indicated that under the normal incidence of a plane wave,

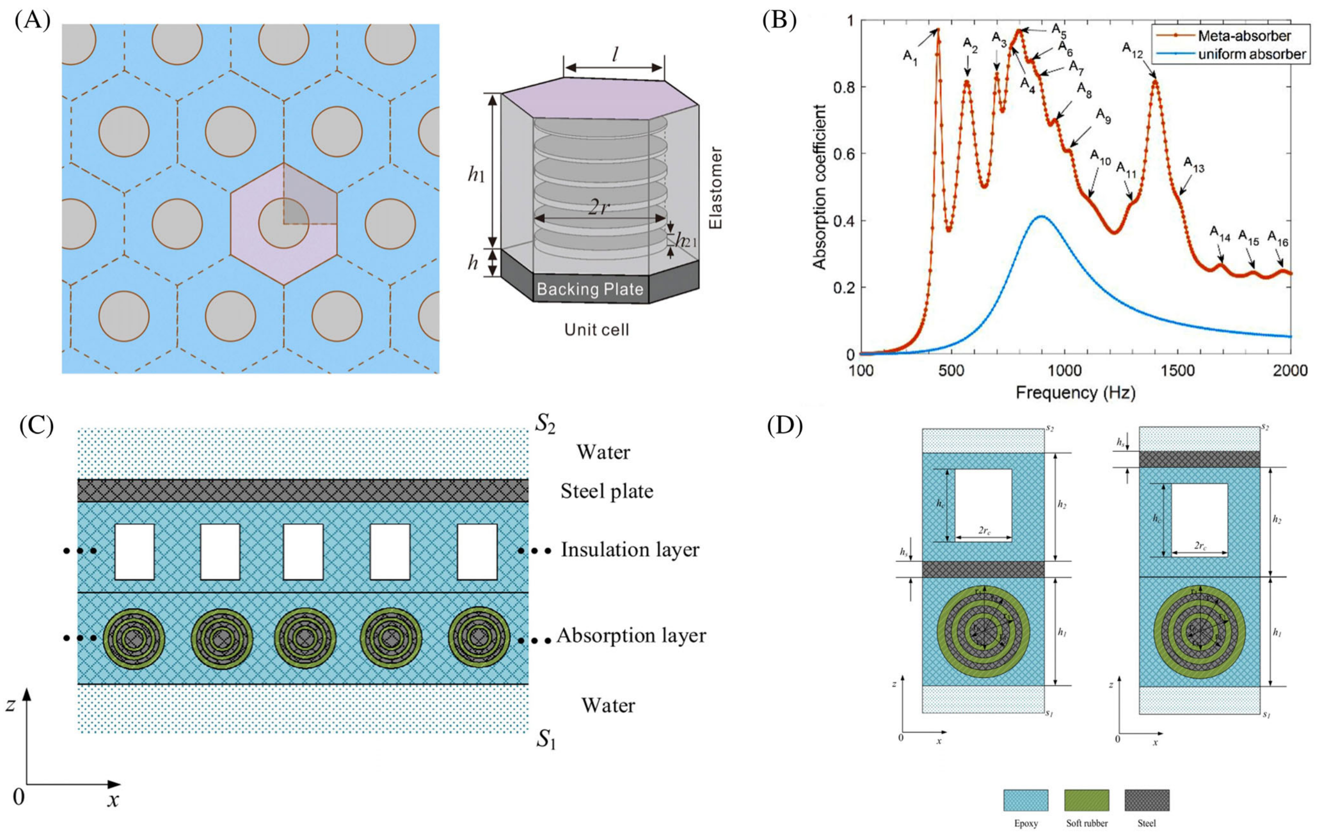

**FIGURE 8** (A,B) An ultra-thin underwater acoustic supermaterial with a thin circular plate uniformly inserted into the elastomer matrix with a thickness gradient and its sound absorption coefficient;[30] (C) schematic diagram of a viscoelastic composite underwater sound absorption structure with multiple vibrators and cavities[32]; (D) single structure of a viscoelastic composite underwater sound absorption structure with multiple vibrators and cavities[32]

the sound absorption performance was perfect, and the sound absorption capacity was high in a relatively wide range. Lee et al.[35] proposed a sound-absorbing hypersurface for underwater sound waves by using the thermal viscosity loss generated by the structure in the acoustic absorption process. As shown in Figure 9A, the surface was prepared by concave, convex orderly carving on the brass block surface. The experimental results showed that the surface had multiple sound absorption peaks in the frequency range of 25–40 kHz and was insensitive to hydrostatic pressure.

### 3.2.2 | Exponential gradient type

By controlling the local refractive index of a metamaterial structure, researchers have achieved a nonresonant loss of sound waves in the metamaterial structure. This type of acoustic metamaterial represents an exponential gradient material. Naify et al.[36] designed an exponential gradient structure consisting of six rubber cylinders with a regular radial distribution in the coating, as shown in Figure 9B. The specific idea was to change the radial radius of a cylinder for the six-layer rubber cylinders to achieve the radial sound velocity gradient change in the coating. However, the wave energy was dissipated when the sound wave reached the center of the coating. In addition, the sound absorption effect of the exponential gradient sound absorption coating was calculated by a multiscattering method. The scattering effect of the sound absorption coating was also examined, and the scattering distributions with and without the rubber cylinder were compared. It was concluded that it had excellent sound absorption performance at all angles. Wang et al.[37] proposed an underwater sound absorption coating with absorbent embedded in the center of an exponential gradient structure. The results showed that the coating could effectively enhance the ability to focus sound to the coating center, reduce the degree of ineffective scattering, achieve a nearly perfect acoustic black hole phenomenon, and ensure a strong absorption effect of underwater acoustic waves in the wide low-frequency bandwidth.

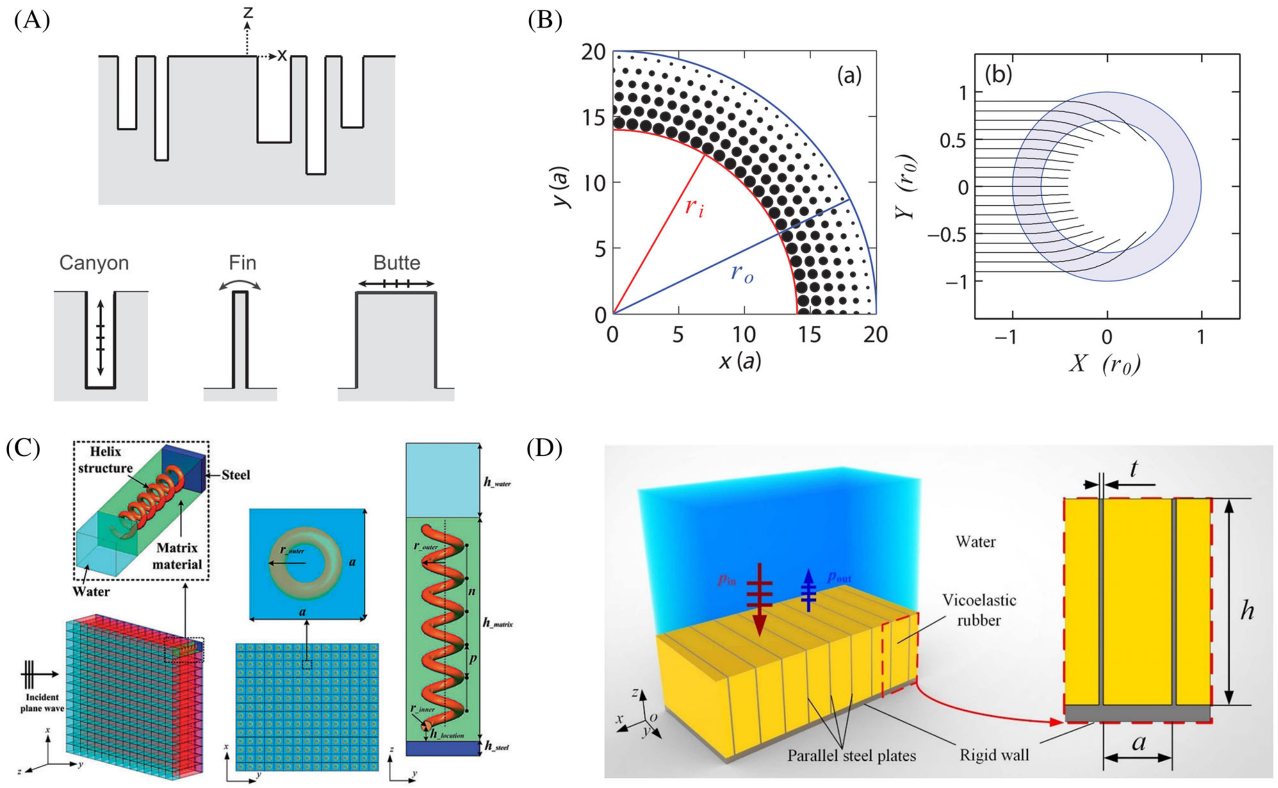

**FIGURE 9** (A) Simplified acoustic hypersurface model for orderly engraving on the surface of brass blocks;[35] (B) radial distribution of rubber cylinders in the coating and sound waves guided to the coating center obtained by the ray tracing method[36]; (C) schematic diagram of the helical metal structure embedded in the underwater sound-absorption material composed of viscoelastic damping rubber;[38] (D) schematic diagram of parallel steel plate composite underwater sound absorption structure inserted longitudinally into the rubber matrix[41]

### 3.2.3 | Other structures

In recent research, a number of underwater sound absorption metamaterials with other structures have also been proposed. For instance, Gao and Zhang[38] reported an underwater sound absorption material with an excellent sound absorption performance in the range of 100 Hz–1 kHz, as presented in Figure 9C. This underwater sound absorption structure was composed of a spiral metal structure embedded in a viscoelastic damping rubber. Due to the spiral metal structure, the propagation mode of a longitudinal wave incident on the material was disturbed, the metal ring interface intensified the destruction of the longitudinal wave, and the waveform conversion response was more significant. In addition, the multiscattering effect on the spiral metal structure and the reflected energy dissipation of the structure were also important sources of acoustic energy dissipation. Gao and Zhang also explored the effects of the outer and inner diameters, the number of turns, the pitch angle, and the construction material of a spiral structure on the sound absorption performance of the underwater sound absorption acoustic metamaterial. Qu et al.[39] designed a composite tungsten-polyurethane impedance-matched underwater sound absorption material with a composite size of only 8.9 mm. The tungsten particles were uniformly arranged in the polyurethane material on a straight line to form a one-dimensional solid structure. Since the addition of tungsten particles made it easier to achieve impedance matching with water, the longitudinal wave velocity in this material was much slower than in the water, and it had better acoustic density at low frequencies, which made it easier to achieve resonance. The sound absorption effect exceeded 90% in the frequency range of 4–20 kHz by using the anechoic tank to test large samples. Wu et al.[40] proposed a spiral underwater sound absorption metamaterial that could adjust the frequency band; the sound absorption mechanism behind the structure was that during the design process, sound waves could not be reflected or transmitted and could enter only the spiral structure for sound energy dissipation. The mechanism was analyzed using the acoustic impedance instead of the wave phase, and the influence of the spiral length, order, and splicing mode on the sound absorption performance was discussed. The simulation test showed that an excellent sound-absorption effect could be achieved in the frequency range of 1–4 kHz with a bandwidth of 2 kHz. Yu et al.[41] designed an underwater acoustic metamaterial with parallel steel plates inserted longitudinally into the rubber matrix to absorb underwater sound waves, as shown in Figure 9D. The results of the theoretical and finite element simulations showed that when the parallel steel plate was involved, the shear deformation at the interface between the steel plate and rubber was significantly strengthened, which greatly promoted the consumption of sound energy. Finally, a theoretical model of plate–rubber interface energy consumption was established and analyzed in depth.

## 4 | CONCLUSION

This paper reviews recent developments in the field of acoustic coatings and comprehensively summarizes the research status of underwater acoustic materials from the aspects of traditional acoustics coating and metamaterial acoustic coating. The traditional coating is based on the cavity and hybridized with various structures to achieve a good sound absorption effect through damping loss, relaxation effect, and waveform conversion. The sound absorption mechanism and the corresponding configuration of metamaterials with local and nonlocal resonances are introduced in detail.

Recent research on the sound absorption coating has made significant progress, but there have still been certain problems, which can be summarized as follows:

1. There has been little research on the sound absorption ability of materials under the oblique incidence condition. The current work has mainly focused on the research of sound absorption ability under the normal incidence of sound waves. However, in practical engineering applications, incident sound waves come from all directions, so further research on sound absorption under oblique incidence is necessary. Although simulation tests under oblique incidence have been performed in a few studies, there have been fewer specific experiments;
2. Research on the sound absorption ability in the frequency range below 1 kHz and a full frequency band has been rare and ineffective. Namely, the current research has been mainly focused on the middle- and high-frequency ranges. Therefore, the research on sound absorption at low frequencies needs further analyses; also, unknown performances of the sound absorption coating at low frequencies need to be explored further. Although there have been various proposals for low-frequency absorption structures, there have still been a few practical ones;
3. There have been fewer reports on the preparation and testing of large samples in an anechoic tank. At present, in the design of underwater material, underwater acoustic tubes have been typically used to test small samples, so it is difficult to evaluate the sound absorption performance of materials in real environments. Therefore, additional anechoic tank experiments are urgently needed to develop underwater acoustic metamaterials with practical engineering prospects;
4. There have been ewer relevant studies conducted under the condition of high static pressure, and further research under high static pressure is necessary to reveal the performance of sound absorption coating under high static pressure. In recent years, various materials and structures have emerged one after another, but there have still been a few high-pressure experiments on them.

Future research should study the development of sound absorption coatings, considering the low-frequency, broadband, high withstand voltage, and all-round efficient sound absorption as important indicators. One of the future development trends could be to develop more effective and innovative sound absorption mechanisms, design theoretical calculation methods for large-scale samples, and combine algorithm optimization with machine learning. The main objective is to apply it under rigorous and complex engineering conditions.

The combination of hybrid structures and cavities and the application of acoustic metamaterials could provide bright prospects in future sound absorption coating development.

## AUTHOR CONTRIBUTIONS

**Zhicheng Zhang:** Writing – original draft (equal); writing – review and editing (equal). **Yanbiao Zhao:** writing and editing. **Nansha Gao:** funding acquisition; investigation; reviewing and editing.

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## CONFLICT OF 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.

## PEER REVIEW

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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