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REVIEW

Review of Underwater Anechoic Coating Technology Under Hydrostatic Pressure

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Abstract

The underwater anechoic coating technology, which considers pressure resistance and low-frequency broadband sound absorption, has become a research hotspot in underwater acoustics and has received wide attention to address the increasingly advanced low-frequency sonar detection technology and adapt to the working environment of underwater vehicles in deep submergence. One the one hand, controlling low-frequency sound waves in water is more challenging than in air. On the other hand, in addition to initiating structural deformation, hydrostatic pressure also changes material parameters, both of which have a major effect on the sound absorption performance of the anechoic coating. Therefore, resolving the pressure resistance and acoustic performance of underwater acoustic coatings is difficult. Particularly, a bottleneck problem that must be addressed in this field is the acoustic structure design with low-frequency broadband sound absorption under high hydrostatic pressure. Based on the influence of hydrostatic pressure on underwater anechoic coatings, the research status of underwater acoustic structures under hydrostatic pressure from the aspects of sound absorption mechanisms, analysis methods, and structural designs is reviewed in this paper. Finally, the challenges and research trends encountered by underwater anechoic coating technology under hydrostatic pressure are summarized, providing a reference for the design and research of low-frequency broadband anechoic coating.

Keywords Anechoic coatings; Underwater acoustics; Hydrostatic pressure; Analysis methods; Structural designs

1 Introduction

The anechoic coating, which is a key component laid on the external surface of underwater vehicles, aims to achieve acoustic stealth performance. This type of coating is a key technology that can simultaneously suppress hull echo and acoustic vibration response, and the acoustic target intensity of underwater vehicles is mainly controlled using an underwater acoustic anechoic coating with strong sound absorption performance (Lane, 1981). The anechoic coating technology typically comprises viscoelastic materials with internal acoustic structures. The design of the underwater anechoic coating must simultaneously satisfy two features to realize good underwater sound absorption performance (Zhu and Huang, 2012). Firstly, the fluid medium and acoustic structure must have excellent impedance matching characteristics to ensure the smooth entrance of sound waves into the structure. Second, the designed acoustic structure displays good dissipation performance for sound energy, enabling maximum dissipation of sound energy entering the structure. Underwater acoustic coatings generally use polymer materials (rubber or polyurethane) as the matrix layer that possess similar water impedance to realize impedance matching between water and acoustic structures (Fu et al., 2021b). In addition, the sound absorption performance is enhanced through the design of acoustic structures, such as cavities, particles, and resonators, within the anechoic coating layer.

Low-frequency sound waves have strong penetration and are not easily attenuated. Thus, efficient absorption of these sound waves for small-sized acoustic structures is difficult. On the one hand, the most widely used types of underwater anechoic coatings currently include acoustic structures with cavities (Wang et al., 2016; Zhong et al., 2019b; Sharma et al., 2020a; 2020b). These coatings can achieve low-frequency sound absorption within 2 000 Hz by utilizing the

Article Highlights

- The research on the acoustic performance of anechoic coatings under hydrostatic pressure is crucial to adapt to the working conditions of underwater vehicles with deep submergence.
- The key factors and sound absorption mechanism of the acoustic performance of anechoic coatings under hydrostatic pressure are studied.
- The research status of analysis methods and structural designs for acoustic performance under hydrostatic pressure are also reviewed.
- The challenges encountered by anechoic coating technology under hydrostatic pressure are summarized, and prospects for future development are provided.

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cavity resonance mechanism, but extending this capability below 1 000 Hz is difficult (Meng et al., 2012; Ye et al., 2018; Zhao et al., 2018; Wang et al., 2021b). The structural strength and hydrostatic pressure resistance are also reduced by the cavity structure. On the other hand, numerous scholars have applied a series of acoustic metamaterials to underwater acoustic structures to improve low-frequency sound absorption and have achieved productive results. Typical ones include locally resonant metamaterials (Zhao et al., 2014; Gao and Zhang, 2018; Shi et al., 2019a; Gao and Lu, 2020; Jin et al., 2020; Zhang and Cheng, 2021), acoustic metasurfaces (Lee et al., 2018; Gu et al., 2021a; Lee et al., 2021a; Liu et al., 2021), diversified acoustic metamaterials (Zhong et al., 2019a; Long et al., 2021; Zhong et al., 2021; Ciaburro and Iannace, 2022; Ciaburro et al., 2022), pentamode metamaterials (Chen et al., 2020; Cai et al., 2022; Cushing et al., 2022; Jia et al., 2023b), chiral materials (Wu et al., 2020; Wu et al., 2021), functional gradient materials (Zhang et al., 2013; Li et al., 2019a; Xie et al., 2020; Shi et al., 2021; Jia et al., 2022), and piezoelectric smart materials (Sun et al., 2015; Zhang et al., 2015; Nguyen et al., 2018; Sun and Hua, 2018; Wang et al., 2023). However, owing to the advancement of modern sonar detection technology (Zhang et al., 2020a) and the rapid development of underwater acoustic signal processing technology (Rahnemoonfar and Rahman, 2016), the working frequency of active and passive sonar continues to extend to low frequencies, and the diving depth of underwater vehicles also continues to increase. The sound absorption performance of underwater anechoic coatings under high hydrostatic pressure necessitates high requirements due to the substantial effect of hydrostatic pressure (Zou et al., 2006; Wang et al., 2020). Additionally, the pressure resistance and acoustic absorption capabilities of underwater acoustic coatings have remained to be a research difficulty and hotspot in underwater acoustics, thus receiving extensive attention and research from numerous scholars (Ma and Sheng, 2016; Wang et al., 2017; Zhang et al., 2020b).

The research and application of underwater acoustic overlay technology are popular topics, but available reviews on these topics are few. Zeqiri et al. (2010) reviewed testing methods for investigating the underwater acoustic characteristics of materials. The development process of sound-absorbing structures from porous materials to acoustic metamaterials was summarized by Yang and Sheng (2017). Zhu et al. (2022) summarized the application directions of underwater acoustic metamaterials, systematically described the current application hotspots, and provided prospects for their future development. A review of the development history of acoustic metamaterials and phononic crystals in recent decades and the introduction of some representative studies, including the calculation of acoustic parameters and the design methods of acoustic metamaterials, were performed by Liu et al. (2020). The advantages of applying acoustic metamaterials to sound-absorbing structures were summarized by Liu et al. (2022) through several typical research examples of acoustic metamaterials, and the current bottleneck issues were then summarized. The authors believe that, despite the remarkable impact of hydrostatic pressure on the acoustic performance of the anechoic coating, relevant review papers that systematically review the underwater sound absorption of anechoic coatings from the perspective of hydrostatic pressure are few. Therefore, underwater anechoic coatings are taken in this paper as the research object, and the relevant research progress of underwater anechoic coatings under hydrostatic pressure is reviewed. The major sections are arranged as follows:

The characteristics, key factors, and main acoustic mechanisms of underwater sound absorption are introduced in Section 2, thereby providing researchers and beginners with the basic concept of sound absorption for underwater anechoic coatings.

The analysis methods of acoustic performance of anechoic coatings under hydrostatic pressure and the current research status of hydrostatic pressure resistance and sound-absorbing structures are reviewed in Sections 3 and 4, respectively.

The challenges and prospects encountered in the current research on underwater anechoic coatings under hydrostatic pressure are summarized in Section 5.

2 Basic concepts of underwater sound absorption

2.1 Physical process of underwater sound absorption

As shown in Figure 1, underwater sound absorption is the process of sound wave penetration through the medium of water and the surface of an acoustic structure, facilitating its subsequent entrance into the structure and enabling absorption (Zhang, 2012). The figure shows that when a sound wave is incident upon the structure from water, the impedance mismatch reflects a portion of the incident sound energy while the remaining energy enters the structure and either continues to propagate or dissipates. The sound absorption coefficient can be defined based on the law of energy conservation (Wang et al., 2021a):

$$\alpha = 1 - \frac{I_r}{I_i} - \frac{I_t}{I_i} \tag{1}$$

where I_i, I_r, and I_t represent the energy of incident, reflected, and transmitted sound waves, respectively. Simultaneously, the reflection coefficient R and transmission coefficient T can be respectively expressed as:

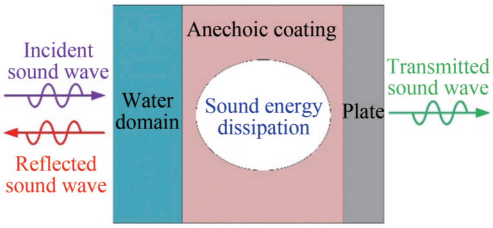


Figure 1 Schematic of underwater sound absorption

$$R = \frac{p_r}{p_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{2}$$

$$T = \frac{P_t}{P_i} = \frac{2 \cdot Z_2}{Z_2 + Z_1} \tag{3}$$

where P_i, P_r, and P_t represent the incident, reflected, and transmitted sound pressures, respectively. Z_1 and Z_2 indicate the acoustic impedance, which is defined as the ratio of incident and transmitted sound pressures to their corresponding normal particle velocities, respectively. These parameters not only depend on the properties of the medium but also vary with the wave propagation direction (Zhang et al., 2021; Zhu et al., 2023). A key parameter in the field of acoustics is acoustic impedance, which is the decisive factor for the performance of underwater sound absorption. The sound absorption coefficient can be further expressed in accordance with Eqs. (1), (2), and (3):

$$\alpha = 1 - R^2 - T^2 \tag{4}$$

The above analysis shows that the sound absorption performance of the structure is closely related to the size of the structure and the acoustic impedance of the material. The acoustic impedance of acoustic material is related to its density and internal sound velocity, as well as to its flow resistance. The performance of sound-absorbing materials is influenced by a flow resistance value. In addition, the temperature, hydrostatic pressure, and medium flow rate of the environment where the acoustic structure is located can affect its sound absorption performance (Liu et al., 2023).

2.2 Calculation and testing methods for underwater acoustics

In the theoretical study of underwater acoustic cladding, numerous methods to calculate its acoustic performance are available, each demonstrating its own characteristics and applicable acoustic structure types. These methods mainly include the transfer matrix method (TMM) (Chahr-Eddine and Yassine, 2014; Lee et al., 2021b), multiple scattering method (MSM) (Li et al., 2006), plane-wave expansion (PWE) (Ponge et al., 2017), finite-difference time-domain (FDTD) (Grinenko et al., 2012; Tsukui et al., 2022), concentrated mass method (CMM) (Bambill et al., 2004), finite element method (FEM) (Hammad et al., 2021; Jiang et al., 2023), and Jacobi–Ritz method (Li et al., 2019b; Pang et al., 2023). The advantages and weaknesses of various typical calculation methods for readers to consider are summarized in Table 1.

Testing of acoustic and mechanical properties is required in the design and evaluation of underwater acoustic structures. Acoustic testing methods mainly include the pulse tube test (Lin et al., 2016), the free-field test (Shi, 2023), and the pressure tank near-field test (Wang, 2021). Meanwhile, the assessment of mechanical strength for these structures largely depends on static compression tests and dynamic thermomechanical analysis. Among them, the pulse tube test facilitates the transmission, propagation, and reception of pulsed sound waves in a rigid, thick wall metal tube filled with water, which is suitable for measuring small-sized cylindrical samples. The free-field test mainly aims to assess the acoustic coefficients of the large-size samples in an anechoic water tank. The pressure tank near-field test is typically employed for the acoustic performance measurement of a structure in a rigid closed tank filled with water. Notably, the most commonly used test method in the measurement of the acoustic coefficient of underwater acoustic structure is the pulse tube test because it is relatively simple and especially suitable for small-size sample tests (Fan et al., 2021; Sun and Hua, 2022)

Table 1 Summary of typical acoustic calculation methods.

Calculation methods	Advantages	Weaknesses
TMM	Simple equation and high calculation efficient	Only applicable to simple one-dimensional structures
MSM	Good convergence and capability to handle special structures (spherical/elliptical)	Only applicable to simple structures
PWE	High precision, versatility, and flexibility	A large difference in component parameters leads to a slow convergence
FDTD	Widely applicable, direct time-domain computing, parallel computing	Numerical dispersion and poor stability
CMM	Simple equation, high calculation efficiency, strong engineering practicality	Uneven distribution of physical parameters, only applicable to simple structures
FEM	Capability to handle complex structures with high computational efficiency, flexibility, and applicability	Large calculation accuracy fluctuates

2.3 Sound absorption mechanism of underwater acoustic structures

2.3.1 Absorption mechanism of traditional underwater acoustic structures

To date, viscoelastic polymer materials, which are represented by cavity resonance, impedance gradient, and particle scattering (as shown in Figure 2), are the basis of the traditional underwater anechoic coating. These materials correspond to multiple acoustic energy dissipation mechanisms, such as viscous dissipation, molecular relaxation, scattering effect, waveform conversion, and resonance effect (Luo et al., 2021). The following text takes several typical acoustic structures as examples to explain the mechanism of acoustic energy dissipation in acoustic structures.

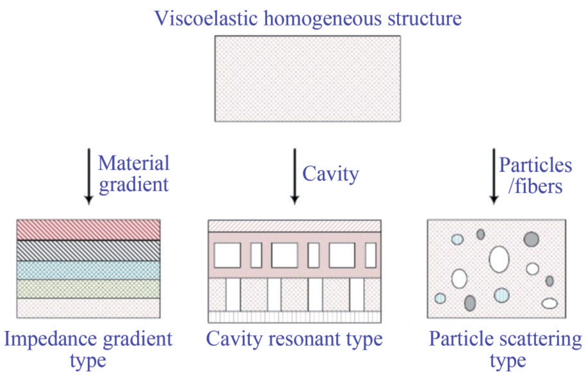


Figure 2 Schematic of traditional underwater acoustic structures

As a type of underwater acoustic functional material, cavity resonant anechoic coating is created by introducing an acoustic cavity structure into the homogeneous sound-absorbing materials. Cavity resonance, waveform conversion, and the intrinsic characteristics of polymer materials are generally used in this type of coating to realize effective sound absorption (Feng et al., 2022). Under the excitation of sound waves, the compression deformation of the material around changes the cavity into shear deformation through the cavity resonance of the structure. This shear deformation is mainly observed around the cavity. Therefore, its sound absorption frequency is related to the natural resonance frequency of the structure. Simultaneously, another main energy dissipation mode of the cavity anechoic coating involves waveform conversion. Waveform conversion occurs when the longitudinal sound wave is incident on the cavity interface, transforming the longitudinal waves into shear waves, which then increases sound energy loss. In addition, important modes of sound wave dissipation include the viscous dissipation, molecular relaxation absorption, and thermal conduction effect of viscoelastic materials (Zhou and Fang, 2022).

The impedance gradient underwater anechoic coating generally comprises homogeneous materials with an impedance gradient (Si et al., 2022). The equivalent impedance of the acoustic–solid coupling surface of this coating matches the characteristic impedance of the water. The acoustic impedance of the structure also gradually increases along the direction of sound wave incidence, thereby increasing the sound energy loss along the thickness direction. This phenomenon can effectively reduce the reflection of sound waves at the acoustic–solid coupling surface and enhance the sound absorption effect of the structure. The viscoelastic internal friction and elastic relaxation process inside the material are used as a basis of impedance gradient underwater acoustic structures to generate losses in sound waves, and their energy dissipation mechanism is similar to that of homogeneous materials (Feng et al., 2020).

Solid particles, solid fibers, or bubbles added to viscoelastic homogeneous sound-absorbing materials are typically involved in the particle scattering underwater anechoic coating, utilizing the interaction between the scatterers and sound waves to realize effective sound energy attenuation (Philip et al., 2004; Haberman et al., 2005). Scattering occurs during sound wave propagation within a structure, thereby altering the propagation path of the sound waves and undertaking waveform conversion, which then converts longitudinal waves with low losses into shear waves with high losses that are effectively absorbed by sound-absorbing materials with viscoelasticity. Therefore, increasing the propagation path of scattered sound waves, waveform conversion, viscous loss, and particle thermal conduction absorption is the sound absorption mechanism of particle scattering acoustic structures. The scattering problem of sound waves is a summary of the theoretical calculation research of particle scattering acoustic structures (Sharma et al., 2019).

2.3.2 Absorption mechanism of underwater acoustic metamaterials

As shown in Figure 3, Liu et al. (2000) proposed localized resonant phonons and originally introduced acoustic metamaterials. They achieved low-frequency elastic wave bandgaps in the sub-wavelength frequency band by utilizing the local resonance effect of elastic waves, thereby introducing new research ideas for low-frequency vibration and noise reductions in small-sized structures. Therefore, the local resonance effect was applied by Zhao et al. (2007) to the design of underwater anechoic coatings for the first time, combining a soft material layer with a hardcore to form a local resonance unit embedded in a rubber matrix (Figure 4). The heavy resonator moves as a rigid body when the excitation frequency of the sound wave is close to the resonance frequency of the local resonance unit. This phenomenon facilitates the generation of shear deformation and the transformation of longitudinal waves into transverse waves by squeezing the soft coating layer, realizing efficient dissipation of the sound wave.

Strict definitions of acoustic metamaterials have not yet

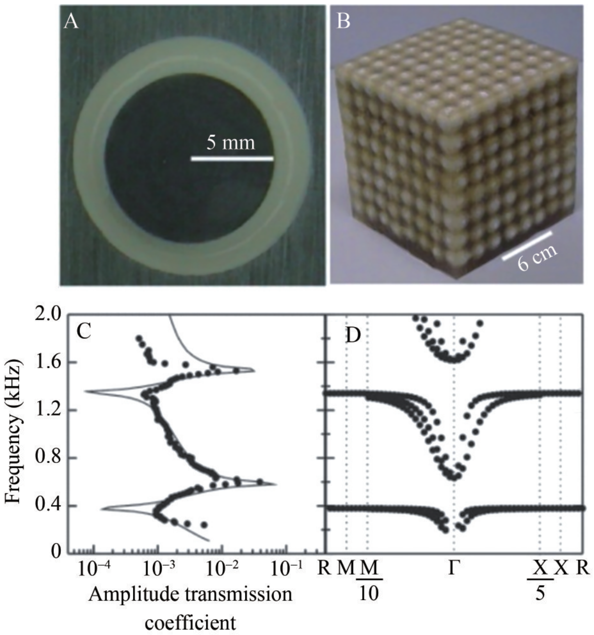


Figure 3 Schematic of local resonance phononic crystals (Liu et al., 2000)

been provided. However, with the deepening of research, the concept of acoustic metamaterials has been further developed, not limited to the single characteristic of using local resonance units for acoustic bandgap regulation. A novel composite material or structural design idea is represented by this concept, which aims to achieve a class of structures with supernormal acoustic properties that are lacking in conventional materials through the ordered design of microstructures at the sub-wavelength physical scale. This concept also aims to develop numerous underwater acoustic metamaterials with multiple sound absorption mechanisms. Chiral materials, pentamode metamaterials, and piezoelectric intelligent materials are typical examples of these metamaterials. Their acoustic action mechanism mainly involves the design of microstructural units and the strange physical characteristics to achieve elastic wave regulation. Several examples of typical acoustic metamaterials are shown in Figure 5.

3 Analysis method of acoustic performance under hydrostatic pressure

Predicting the acoustic performance of underwater anechoic coatings through accurate and efficient modeling and analysis methods is crucial. However, current studies on underwater anechoic coatings are performed under normal pressure. Meanwhile, underwater vehicles operate in deep water, which is guaranteed to be influenced by high hydrostatic pressure. Moreover, their shapes and material parameters will change, leading to a considerable impact on sound absorption performance. Therefore, a research hotspot in underwater acoustics lies in the incorporation of the influence of hydrostatic pressure into the analysis and calculation of the acoustic performance of underwater acoustic coatings. Such an approach is also a major challenge in the current design of underwater anechoic coatings.

The influence of coating deformation on sound absorption is mainly considered in the current study of underwater anechoic coatings under hydrostatic pressure. Jiang et al. (2006) (Figure 6(a)) and Tao and Zhuo (2011) (Figure6(b)) used the underwater acoustic structure with cavities as the

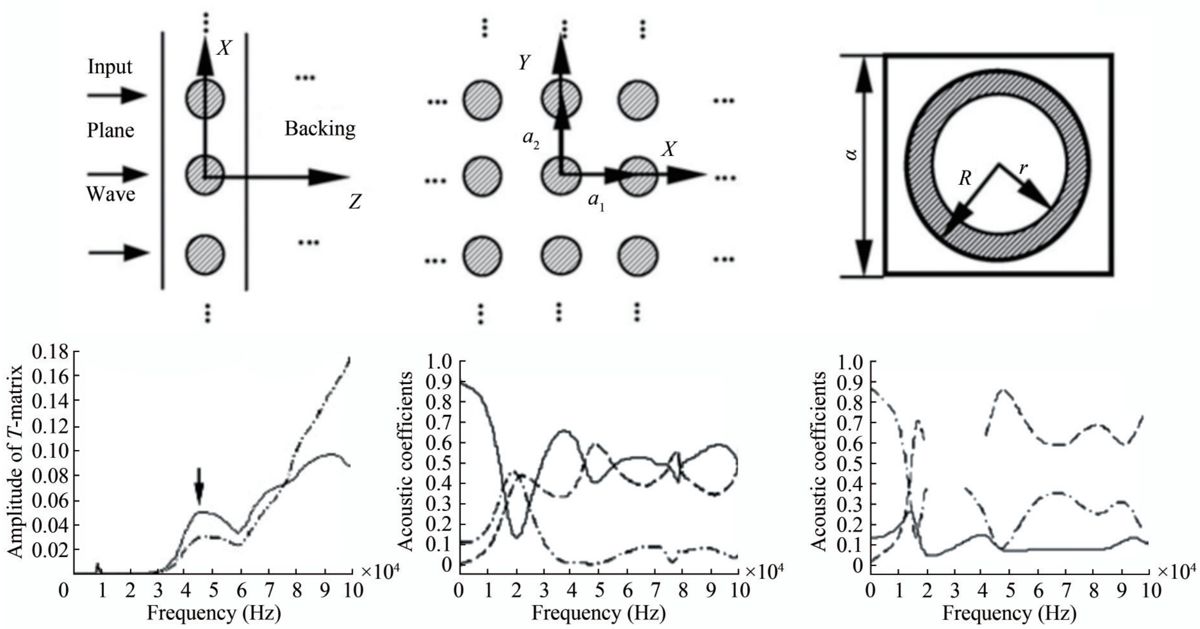
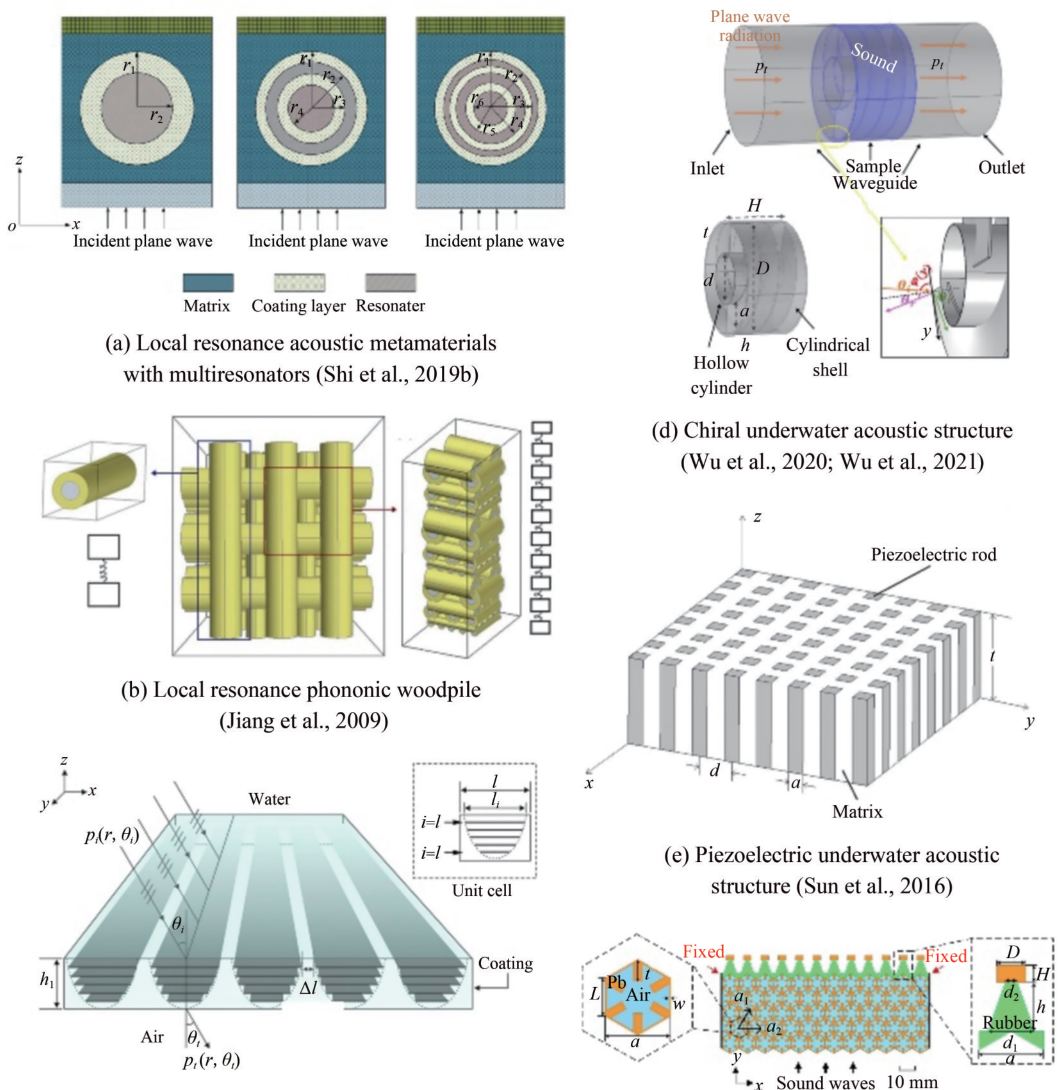


Figure 4 Underwater anechoic coating with local resonance unit cell and their acoustic properties (Zhao et al., 2007)



(a) Local resonance acoustic metamaterials with multiresonators (Shi et al., 2019b)

(b) Local resonance phononic woodpile (Jiang et al., 2009)

(c) Underwater acoustic structures with thin gradient plate scatters (Zhang et al., 2018)

(d) Chiral underwater acoustic structure (Wu et al., 2020; Wu et al., 2021)

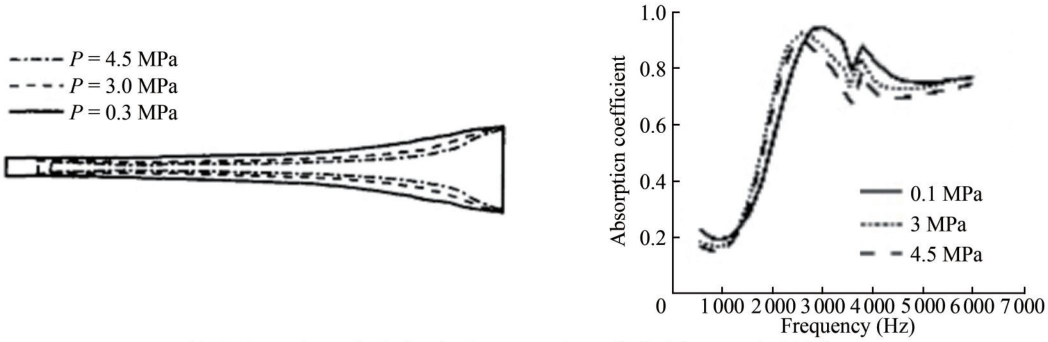
(e) Piezoelectric underwater acoustic structure (Sun et al., 2016)

(f) Pentamode acoustic metamaterials (Gu et al., 2021a)

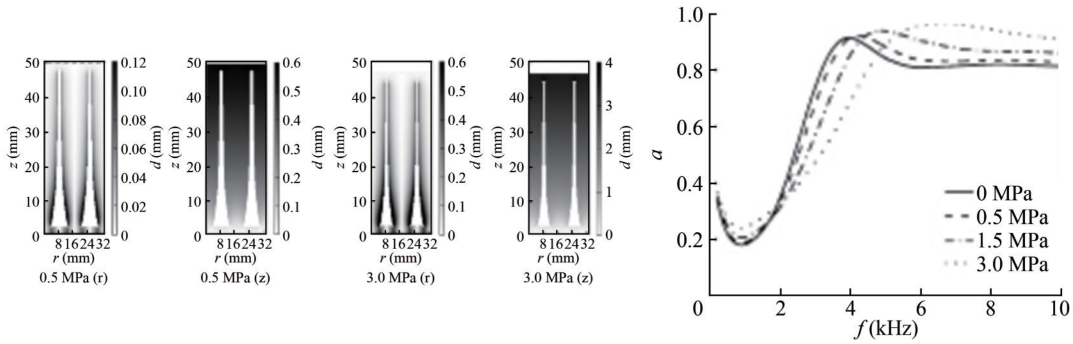
Figure 5 Several examples of typical acoustic metamaterials

research object and studied the structural deformation under hydrostatic pressure. Then, they investigated the change law of the acoustic performance of the structure under different hydrostatic pressures by employing the finite element method. Research has shown the movement of sound absorption bands toward high frequencies with the increase in hydrostatic pressure. The corresponding relationship between the effective volume of the cavity and the frequency band of the sound absorption curve is observed based on their results.

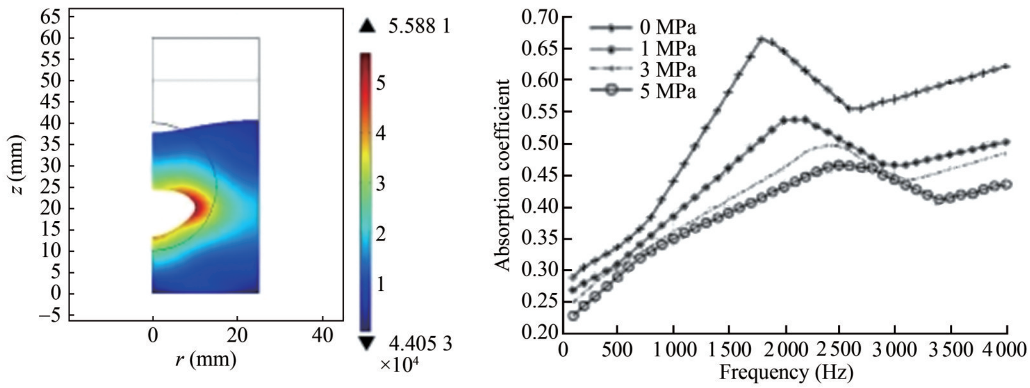
The acoustic performance of the structure under hydrostatic pressure can be effectively analyzed via deformation analysis followed by acoustic calculation, but difficulties are encountered in the modeling and calculation processes. Therefore, Zhang et al. (2017) and Chen et al. (2022) directly calculated and analyzed the sound absorption effect of the anechoic coating with spherical cavities based on the structural compression deformation by using the moving grid modeling method (Figure 6(c)). Improvements in the previous calculation method of first calculating the structural deformation and then re-modeling, simplification of the modeling process, and provision of a simple method for the follow-up work are realized through the obtained results. Considering the effect of hydrostatic pressure, Shi et al. (2023a) and Jia et al. (2023a) also established the acoustic structure coupling finite element equation by adding the potential energy term generated by hydrostatic pressure into the acoustic structure coupling finite element. The universality of the traditional finite element method for hydrostatic pressure analysis of acoustic structures can be expanded through this approach. Dong and Chen (2021) studied the sound absorption performance of anechoic coatings under



(a) Deformation calculation before acoustic analysis (Jiang et al., 2006)



(b) Deformation calculation before acoustic analysis (Tao and Zhuo, 2011)



(c) Moving grid modeling method (Zhang et al., 2017; Chen et al., 2022)

Figure 6 Influence of structural deformation under hydrostatic pressure on the sound absorption performance.

hydrostatic pressure considering the influence of cavity pressure on deformation. The simulation results show that the effect of cavity pressure on the acoustic performance of the acoustic absorber becomes highly significant as the hydrostatic pressure increases. In further research on the influence of hydrostatic pressure on the cavity inside the coating layer, Yang et al. (2022a) introduced a linearization analysis theory that considers the large static prestress and pre-deformation of the coating. They comprehensively evaluated the deformation field and incremental constitutive tensor and explained the physical mechanism of structural deformation under hydrostatic pressure. In addition to the deformation of the cavity, the results indicate that the changes in constitutive tensors due to prestressing and pre-deformation also influence the sound absorption effect of the structure.

Deformation of the structure and effects on the material parameters of the structure can be attributed to the hydrostatic pressure. However, mature theoretical and empirical formulas for the changes in material parameters under hydrostatic pressure are unavailable, and experimental research remains the main focus. A measurement method for the dynamic mechanical parameters of rubber materials under hydrostatic pressure in a hydroacoustic tube, which has high testing accuracy and a wide testing frequency range, was established by Huang et al. (2013). Comparison results between the calculated acoustic absorption coefficient and the experimental results based on the measured material parameters confirmed the effectiveness of the method. This method successfully supports investigations on the mechanism of acoustic coating and acoustic design under hydrostatic pressure. Furthermore, a measurement method for

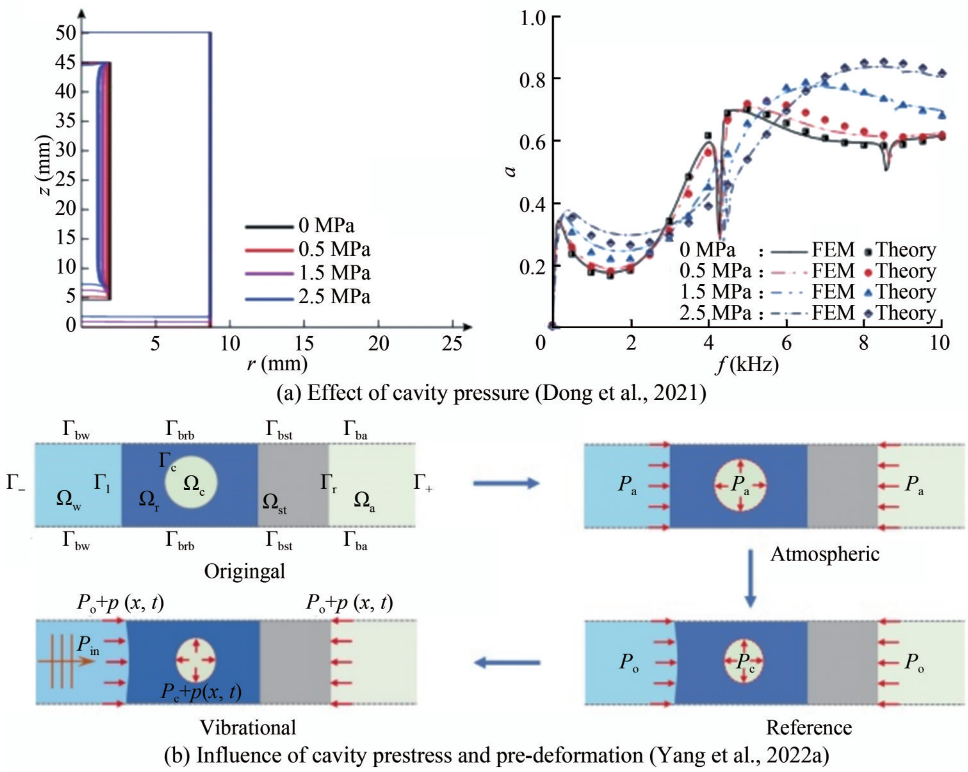


Figure 7 Influence of the cavity on the anechoic coating under hydrostatic pressure

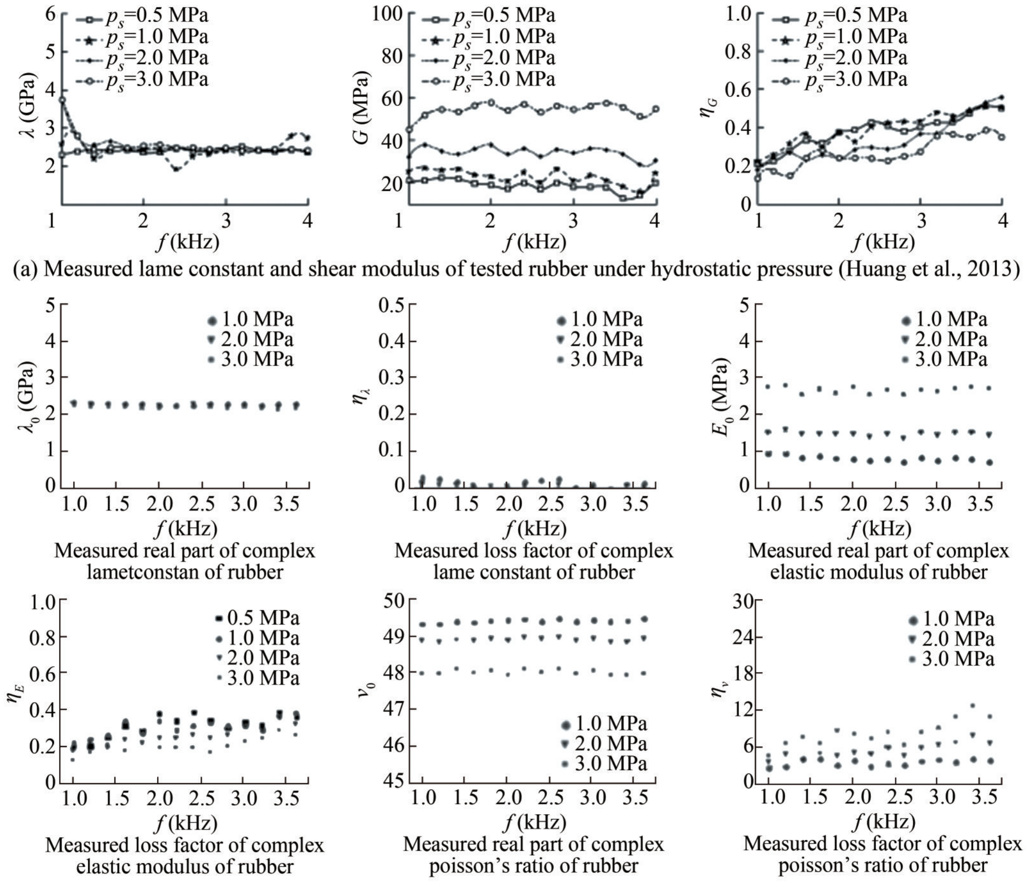
the viscoelastic dynamic parameters of polymer materials under static pressure was introduced by Tao (2016). The influence of hydrostatic pressure on viscoelastic dynamic parameters was analyzed and summarized. The acoustic coefficient of the acoustic coating under static pressure was measured and compared with that calculated with measured material parameters to verify the method.

Overall, the influence of hydrostatic pressure on the anechoic coating causes structural deformation and the material parameters. Considering changes in structural deformation and material parameters when examining the sound absorption effect of acoustic structures under hydrostatic pressure is necessary. Research in this area is currently limited, and studies on the acoustic performance of anechoic coatings under hydrostatic pressure typically involve experiments (Humphrey et al., 2008; Audoly, 2011; Gu et al., 2021b; Gao et al., 2022; Tang et al., 2022; Gao et al., 2023; Ren et al., 2023). Therefore, theoretical and computational approaches to the acoustic performance of anechoic coatings under hydrostatic pressure are still required.

4 Design of acoustic structures resistant to hydrostatic pressure

The diving depth of underwater vehicles is also constantly rising to address the increasingly advanced sonar detection, putting high requirements on the structural strength and acoustic performance of their surface anechoic coatings. The design and research progress of pressure-resistant underwater anechoic coatings has been slow due to the lack of guidance from new design principles, thus becoming a bottleneck problem that must urgently be addressed for acoustic stealth of underwater equipment. In particular, a scientific and engineering problem lies in the realization of an acoustic coating with good acoustic performance and hydrostatic pressure resistance.

The matrix of the traditional anechoic coating mostly comprises a rubber material, which has a low modulus and is prone to considerable deformation under high hydrostatic pressure. Hence, Su et al. (2022) included Eucommia rubber into the viscoelastic matrix of the covering layer, which effectively improved the pressure resistance and sound absorption performance of the pure rubber matrix. Fu et al. (2021a) added carbon nanotubes and graphene nanosheets to improve the pressure resistance and sound absorption performance of polydimethylsiloxane (PDMS). Overall, from the perspective of matrix material modification, these methods improved the pressure resistance of the structure. Shi et al. (2023b) mixed inorganic fillers into rubber materials and combined them with traditional acoustic structures to utilize the characteristics of functionally graded materials, thereby forming a composite functionally graded anechoic coating. The designed composite structures not only markedly improve the pressure resistance performance



(a) Measured lame constant and shear modulus of tested rubber under hydrostatic pressure (Huang et al., 2013)

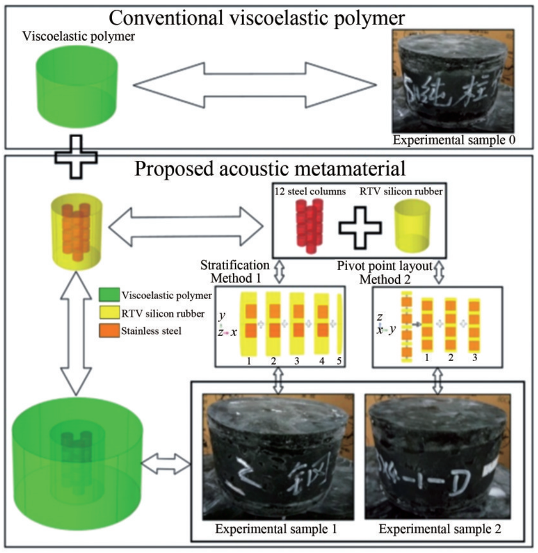
(b) Rubber material parameters for experimental testing (Tao, 2016)

Figure 8 Experimental measurement of material parameters of acoustic structures under different hydrostatic pressures

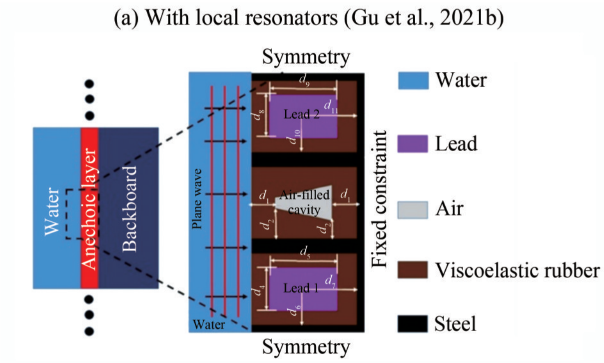
but also realize a good low-frequency broadband sound absorption effect based on the numerical calculation.

Considering the design of the anechoic structures, Gu et al. (2021b) used experimental methods to analyze the performance of anechoic coatings with local resonance units to confirm that the absorber with local resonance units can achieve improved low-frequency sound absorption under hydrostatic pressure. Feng et al. (2022) designed a pressure-resistant acoustic composite structure with coupling of multiple acoustic mechanisms. On the one hand, the underwater sound absorption performance is improved by the coupling effect of local and cavity resonances. On the other hand, the deformation of the rubber and cavity caused by hydrostatic pressure can be effectively reduced by supporting the metal wall connected to the backing, thereby enhancing the strength of the structure. Yang et al. (2022b) revealed that the addition of aluminum hollow cylindrical supports around the cylindrical cavity not only effectively improved the hydrostatic pressure resistance performance of the structure but also enriched the sound absorption mechanism of the structure and enhanced the sound absorption performance under hydrostatic pressure. Li et al. (2023) enhanced the structural strength by designing an underwater acoustic structure containing a rubber sandwich with a funnel-shaped cavity and adding carbon fiber columns as reinforcement materials. They also introduced local resonance units into the structure to further improve the sound absorption performance of the designed structure under hydrostatic pressure.

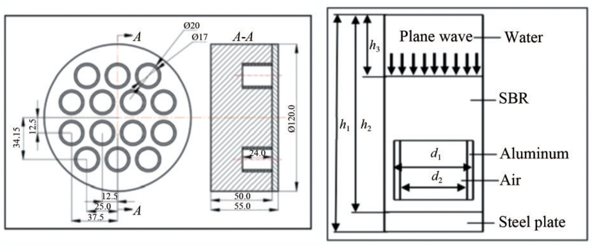
Researchers have also explored various design schemes for microstructure units of underwater acoustic materials to improve their compressive strength. Jiang and Wang (2012) introduced interpenetrating network structures into local resonant phononic crystals to construct phononic glasses with broadband, strong sound absorption, and pressure resistance properties. This structure demonstrates good sound absorption performance in the mid-high frequency range and good compressive strength under high hydrostatic pressure. However, a disadvantage of this structure lies in its poor low-frequency sound absorption. Zhong et al. (2019a) studied the underwater sound absorption performance and bandgap characteristics of the structure by developing an underwater acoustic ultrathin metamaterial plate, which combines particle-filled polyurethane damping material and spiral-based local resonance mechanism. Research showed the weakening effect of high hydrostatic pressure on the attenuation of underwater sound absorption performance of sound-absorbing materials due to the local resonance



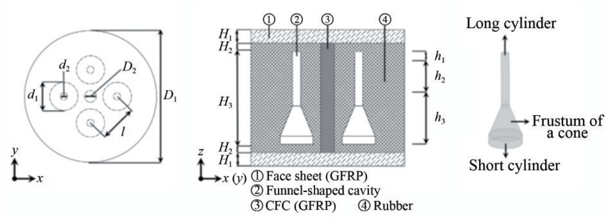
(a) With local resonators (Gu et al., 2021b)



(b) With metal support (Feng et al., 2022)



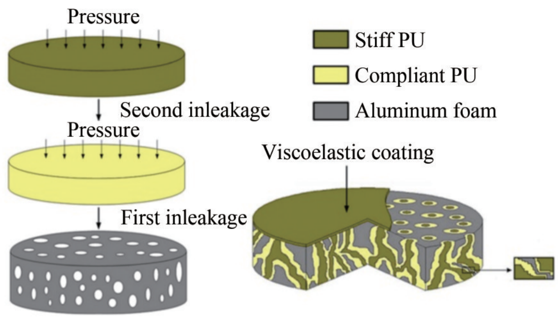
(c) With wall support cavity (Yang et al., 2022b)



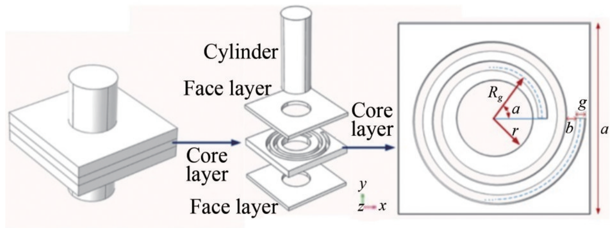
(d) With carbon fiber support column (Li et al., 2023)

Figure 9 Design of underwater anechoic coatings considering hydrostatic pressure conditions

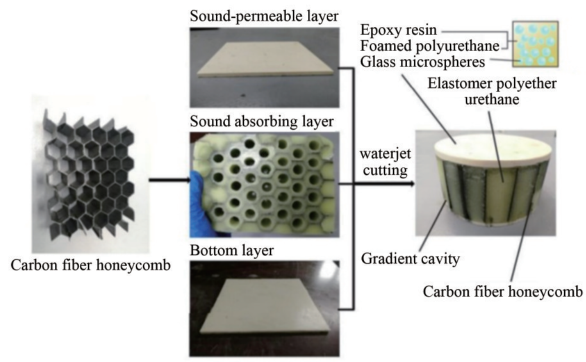
band gap. This study revealed specific structures that can be used to enhance sound absorption while minimizing the impact of static pressure on acoustic performance. Wang et al. (2020) used carbon fiber honeycomb structures as skeleton supports with cavity acoustic structures due to the excellent compressive strength of honeycomb structures and designed a periodic sound-absorbing array structure based on the combined effects of cavity resonance and impedance conversion. This structure can display a good broadband sacrificial effect under hydrostatic pressure.



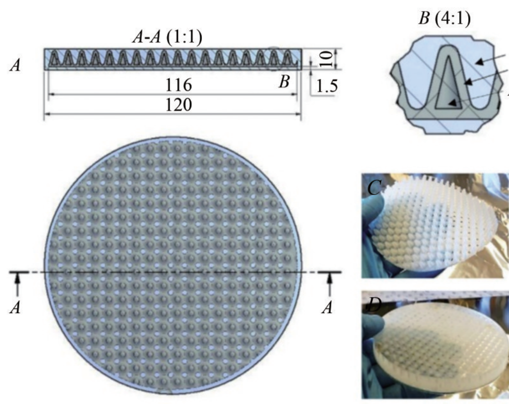
(a) Phononic crystal (Jiang and Wang, 2012)



(b) Spiral resonator (Zhong et al., 2019a)



(c) Honeycomb support structure (Wang et al., 2020)



(d) 3D-printed structure (Baena et al., 2023)

Figure 10 Design of microstructural units for hydrostatic pressure-resistant

Overall, the sound absorption performance under hydrostatic pressure can be improved by using complex acoustic structural designs. However, the remaining engineering challenge lies in the processing of the designed acoustic structure. Baena et al. (2023) designed a thin film acoustic metamaterial with periodic conical cavities by utilizing 3D printing technology and using several different types of polyurethane as the main material. Compared with pure materials, the designed metamaterial demonstrates stable sound absorption performance under hydrostatic pressure. Meanwhile, defects within the polymer can be minimized by improving the 3D printing parameters, further enhancing the structural performance. This study introduces research ideas for realizing complex acoustic structures.

5 Conclusion and Outlook

Underwater anechoic coating technology is the basis and critical support for the development of marine equipment, demonstrating broad application and development prospects. Deep submergence has become an important development trend for underwater vehicles due to the constantly evolving sonar detection technology, therbey placing high requirements on the acoustic performance of underwater anechoic coatings under hydrostatic pressure. Considering the influence of hydrostatic pressure on underwater acoustic coatings, this review surveys the research status of underwater acoustic structures under hydrostatic pressure from the aspects of sound absorption mechanisms, analysis methods, and structural designs. Some breakthroughs have been realized in the research of underwater anechoic coatings under hydrostatic pressure. However, the actual demand for acoustic stealth of underwater vehicles under deep submergence conditions, especially in realizing low-frequency broadband sound absorption of the coating under high hydrostatic pressure, still requires a considerable amount of work. Overall, the design and research of anechoic coatings still need to be explored in several aspects as described below:

On the one hand, the low-frequency broadband sound absorption effect of the anechoic coating is not ideal, especially under the influence of high hydrostatic pressure, and the low-frequency sound absorption effect generally deteriorates. Current research on underwater acoustics mainly centers on the mid-high frequency range, and research on low-frequency broadband sound absorption is relatively limited. In particular, research on controlling low-frequency acoustic waves below 1 kHz under hydrostatic pressure is still limited.

On the other hand, theoretical analysis and calculation methods that comprehensively consider the acoustic performance under hydrostatic pressure are lacking. Most theoretical studies currently only consider the deformation of structures under hydrostatic pressure, overlooking changes in material properties or geometric deformation of materials under static pressure. The geometric deformation of structures and the change in matrix parameters are combined under hydrostatic pressure. Therefore, establishing precise acoustic analysis models and analysis methods under high hydrostatic pressure is still necessary.

Moreover, research on large-scale sample production and testing is lacking. The processing capacity for large-sized and structurally complex acoustic components is currently insufficient due to the limitations of the technological level. Underwater acoustic testing mostly involves small sample testing in water-filled tubes, and demonstrating the sound absorption capability in real environments through the test results is difficult. In particular, reports on underwater acoustic tests under high hydrostatic conditions are few.

In addition, the design of acoustic structures that can effectively balance high-voltage resistance characteristics and low-frequency broadband sound absorption necessitates in-depth research. An effective approach to solving the problems in this field lies in the design of small-sized, lightweight, and high-pressure-resistant low-frequency broadband acoustic structures, which involves utilization of the extraordinary physical and structural characteristics of acoustic metamaterials. This approach is also an important direction for future research on underwater acoustic cover layer technology.

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