Review of underwater sound absorption materials

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Abstract. Underwater sound absorption is becoming more and more important for underwater military equipment. Underwater acoustic stealth technology is constantly developing, we have conducted a research, summary and classification of underwater sound stealth materials. There are mainly four kinds of underwater acoustic stealth materials: porous materials, resonance materials, piezoelectric materials and metamaterials. We also studied the sound stealth mechanism of these materials.

1. Porous materials
Porous materials mainly cover the foam, sponge, porous material. Underwater sound absorption porous materials are mainly perforated metal materials, porous polymer materials and fibrous metals. Foam is the most cost-effective and convenient of commercially available acoustical materials, which can be used to transmit and absorb sound by appropriate design of its pore structure. Under the action of the incident sound pressure, the pore medium will vibrate, and cause acoustic wave hit the cell wall, generate diffuse and erasure, and pore medium will occurrence compression stretching deformation at the same time. Based on the above mentioned phenomena, the acoustic energy is mainly dissipated due to friction and heat transfer.

The influence of porous structure of porous aluminium on its sound absorption performance was studied by Cheng et al. When the aperture decreases from 5 mm to 2 mm, the porosity and sound absorption performance can be optimized. Generally, the best porosity is 75-80%. The thicker the specimen, the better the sound absorption [1, 2]. Non-metallic porous underwater acoustic materials include open polyolefin (PO), SIC foam and open cell polyurethane (PU) foam. In the same way, the aperture and thickness have an effect on the sound absorption coefficient [2]. Compared with PU open cell foam, the PO foam has high bending and airflow resistance, so it’s mid frequency sound absorption performance is better [3]. Wang Yue et al. shown that open pore foamed aluminium with different pore structures have higher underwater sound absorbing coefficient, and that the underwater sound absorbing properties are attributed to their pore structures. When the pore size decreases, or the porosity and the thickness increase, the underwater sound absorbing properties will be improved [4]. The broadband sound absorption performance can be obtained by stacking varies pore structure. In order to improve the low frequency sound absorption performance, cylindrical inclusions can be inserted into the matrix [5]. Wang H et al. investigated the sound absorption properties of the open-celled aluminium foams prepared by the counter-gravity infiltration casting method and traditional process. They found that all the samples prepared by two kinds methods have the uniform change trend, the sound absorption property is better in high frequency region than that in low frequency region. But the sample prepared by the former method has a better absorption property, which is due to the decrease of connected space between adjacent holes in counter-gravity infiltration casting. The sound absorption coefficient of open-cell
aluminium foam prepared by counter-gravity infiltration casting method increases with the particle size decreasing and with the porosity and thickness increasing [7]. M Furstoss et al. argue that the active passive hybrid system can be used to improve the sound absorption performance, which can reduce the complexity of the system, and the traditional dissipative materials can be used [8]. Wang et al. extended a model of sound absorption for perforated plates with through-holes to make it applicable for common porous materials [9].

Porous materials have good sound absorption properties, mechanical properties and easy manufacturability, so it is used for underwater sound absorption. The porous material is complex and contains many parameters, such as pore size, thickness, porosity, flow resistance, solid phase density etc. Different parameters have different effects on the sound absorption. Compared with closed cell materials, open cell materials have better sound absorption performance because of the high flow resistance. Generally speaking, the sound absorption property increases with the increase of material thickness. Introduce some inclusions in porous materials can improve the sound absorption properties. Tang Huiping et al. studied the sound absorption coefficients of gradient porous materials with different pore structure, the gradient structure were assembled in different ways, using two or three layer samples with different porous characteristics. They confirmed that the gradient structure greatly improves the sound absorption coefficient at low frequency. In the precondition that the arrangement from high porosity to low porosity is beneficial to improve the sound absorption coefficient, the higher the porosity and the thicker the thickness, the better the sound absorbing characteristics of the gradient structure[10].

There are few researches on the application of porous materials under water, for the impedance mismatch is a major disadvantage of porous materials. The theoretical model for analysing the acoustic properties of porous materials in atmospheric environment is not suitable for underwater. When the porous material is chosen as the underwater silencer, we should pay more attention to its surface impedance. Although there are active control methods to modulate impedance, but extremely complex and difficult to implement.

2. Resonance Materials

Resonant sound absorption material is a hot topic that people have been studying for a long time. Early in World War II a rubber covering layer with an air chamber was developed by German engineers. Now there are a large number of researchers investigate the underwater acoustic absorption properties of various materials with various cavity, and various inclusions. The existence of gas cavity provides a monopole resonance, and the existence of inclusion provides a dipole resonance. If the inclusions and cavities are periodic arrangement in matrix, the material will achieve a good sound absorption effect by the multiple scattering effects and the wave mode conversion. We can use the inclusion of different sizes or different materials to obtain more than one resonance frequency to broaden the absorption frequency band, even improve low frequency sound absorption properties. Resonant sound-absorbing materials can be divided into three types: cavity resonance [11-19], inclusion resonance [20-22], and multi-member local resonance [23-30].

Faced with the problem of underwater acoustic absorption at low frequency, quite a few people argue that embed resonance inclusions in rigid, low-density, water impedance-matched, elastic hosts is a good choice. The research on the sound absorption characteristics of viscoelastic materials with cylindrical holes shows that the resonance of the cavity can significantly improve the sound absorption performance [11]. It is found that the position of the cavity is independent of the sound absorption, and there is a wave type conversion at the cavity [12]. Using the theory of multiple scattering and energy band, the sound absorption performance of periodic cavity structure can be studied, Ivansson has done some research about numerical design of alberich anechoic coatings with super ellipsoidal cavities of mixed sizes[13]. Some people have studied thin rubber coatings with super ellipsoidal cavities in a doubly periodic lattice [14]. The dynamic response of a single cavity can be analysed by Mie scattering. The homogenization method combined with the finite element method can also be used to analyse the sound absorption performance of the cavity structure, Sharma and G. S found that the resonance response of
cavity monopole leads to the maximum absorption. [16]. David C. Calvo et al. found the drum respiratory resonance of the disk cavity can achieve low-frequency sound absorption [18].

For the sound-absorbing materials applied to the surface of underwater submarines or other vehicles, there are also vehicle structures at the back, such as skin stiffeners, which will also affect the performance of the sound-absorbing materials, especially the low-frequency sound-absorbing performance. Fu X.Y. et al. studied this case through Bloch periodic boundary condition [15, 19].

We should realize that the structure is easily deformed under hydrostatic pressure because of the presence of gas in the matrix, the structure can be compressed, further lead to sound absorption performance change. Considering that the cavity structure in viscoelastic material is easy to deform and affect the design frequency under the hydrostatic pressure, it can be replaced by a rigid inclusion, which ensures the rigidity of the structure [20]. In the same case, hollow glass balls can be considered when filling inclusions, which also have better strength and reduce certain weight [21, 22].

Lim et al. proposed a structure, which consists of three members, embedded with lead coated silica gel balls in epoxy resin, and the shear mode conversion at the inclusion site is beneficial to energy dissipation [23]. Wen J et al. proposed a local resonance model with ellipsoidal inclusions. The first absorption peak of the structure is from the local resonance of the structure, and the second absorption peak is from the modal transformation of the structure [24]. Zhao H et al. studied the local resonance thin plate with three component inclusions, and also found that the mode transformation at the local resonance has a great effect on the improvement of the sound absorption performance [25]. Through the analysis of Mie scattering matrix elements, the physical mechanism of low-frequency absorption is studied. It is found that the scattering energy tends to stay in the shear wave, which enhances multiple scattering, and the sound energy will decays rapidly in viscoelastic polymer [26]. Jiang H et al. introduced woodpile structure into locally resonant phononic crystal (LRPC) and fabricated an underwater acoustic absorbing material named LRPW, which has a strong capability of absorbing sound in a wide frequency range. They studied the mechanism of strong sound absorbing of the LRPW by the lumped-mass method [27]. The influence of IPN microstructure on the performance of underwater acoustic stealth is studied. The microstructure, phase separation degree, phase size and phase continuity of IPN were analysed. The results show that IPN with continuous and uniform nano-phase has high absorption coefficient [28]. In addition to the strong dissipation of sound energy caused by local resonance, the backing materials sometimes produce coupling vibration, so there are two resonance responses, two absorption peaks for those periodic structures with backing medium [29]. Based on the concept of local resonant phonon crystal, the interpenetrating network glass structure is proposed. Due to the difference of microcosmic size, it is equivalent to the collection of more local resonant oscillators of different sizes, so as to realize the broadband sound absorption performance [30].

In summary, the Mie scattering method can be used to study the acoustic scattering of a single structure, while for periodic structures, the band structure can be calculated by using the Bloch periodic boundary conditions and the finite element method. The resonance frequency of the material is further obtained from the band structure. The above mentioned research is mostly theoretical research, only a few papers related to the inclusion structure to hydrostatic pressure, stiffness sensitivity. At the same time, the skin rib structure of the underwater vehicle will also affect the sound absorption performance of the material [31, 32]. As a whole, the development of resonant sound-absorbing materials is changing from a single discrete form of inclusion structure to a continuous hybrid structure, and the manufacturing difficulty of this material is also increasing.

3. Piezoelectric Materials And Active Control
Piezoelectric materials are used widely, such as ultrasonic generators, filters, sensors, and actuators. Due to the piezoelectric effect, piezoelectric materials can be made into the transducer, applied to underwater sound absorption structure.

Cai J et al. prepared a new type acoustic absorbing composite based on piezoelectricity and electrical conductivity theory. They studied the energy dissipation mechanism of piezoelectric and absorption route of composite. They found that the sound absorption coefficient is greater than the value before the
polarization, which indicates that the piezoelectric properties play an important role in sound absorption. They also shown that the acoustic absorption property of piezoelectric and conductive composite is improved on certain level by the addition of electrical conductivity phase [33]. Zhao H et al. proposed a bi-laminated piezoelectric plate. It consists of an elastic layer in contact with water and an earthed vacuum piezoelectric layer. They formulated the required electric potential across the piezoelectric layer to cancel the reflection from the fluid/elastic boundary for the piezoelectric material PZT-5 at various thickness parameters and incident frequencies [34]. C.L.Scandrett et al. confirmed that the combination of piezoelectric material and viscoelastic material can enhance the sound absorption effect compared with viscoelastic material only [35]. The thin-walled polymer collectively covered with a flexible piezoelectric ceramic or 1-3 piezoelectric composite coating can be used for sound absorption [36]. Some specific structures of piezoelectric materials can modulate acoustic impedance. The 0-3 type piezoelectric composite material with negative capacitance circuit can realize the wide frequency modulation of the underwater sound absorption spectrum. The transfer matrix method of plane wave propagation can be used for numerical analysis of such materials [37].

Forward proposed piezoelectric shunt damping technology in 1979. The piezoelectric shunt damping technology has been applied in the vibration control and sound absorption since its stability, simplicity, low cost and easy installation. The incident sound energy is converted to electrical energy by piezoelectric materials, and then the shunt circuit converts electrical energy into heat dissipation [38]. Different shunt circuit has different effect on sound absorption effect. L-R shunt circuit will generate a complete gap, whose bandwidth is independent of the direction of the wave. The shunt circuit formed by piezoelectricity layer connecting single resistance and inductance can achieve narrow frequency sound absorption. In order to broaden the absorption spectrum, it needs the existence of a variety of shunt circuits, which requires the existence of multiple R-L circuits. At the same time, adjusting the values of resistance and inductance elements in the circuit can realize the shift of sound absorption frequency band [39]. If the piezoelectric are arranged periodically, they can also be regarded as phononic crystal materials. The energy band structure can be studied through the theory of energy band and Bloch's principle. The elements connecting the circuit on the piezoelectric have obvious influence on the energy band structure. Chen S et al. found that the existence of these circuits makes the band structure open a band gap, that is, the absorption band [40].

In addition to the sound control at the material level, there is also the sound control at the system level. An active sound absorption method is based on the principle of destructive interference between waves. The acoustic energy in local region can offset each other, so as to achieve the purpose of zero reflection. In generally, it needs special control system, including sensor, actuator, and control circuit.

The active control system of the adaptive digital controller can also be used for the coating of underwater equipment. Through the monitoring system and the control system, the wide frequency band non echo effect can be achieved [41]. Tang J et al. put forward an intelligent foam, which is composed of PVDF and polyurethane foam. The sound absorption benefits from the dissipation mechanism of polyurethane and the active output excitation of PVDF by the oscillating circuit [42]. In order to reduce the acoustic reflection on the surface of underwater objects, Howarth, T.R. et al. Proposed a novel control strategy, in which two kinds of piezoelectric elements are installed in the coating, namely piezoelectric actuator and piezoelectric sensor. The sensor senses the external sound wave and converts it into an electronic signal to the control circuit. The control circuit commands the driver to make appropriate response, so as to match the surface impedance of the object with the incident interference [43]. Cai C et al. put forward a kind of multilayer active sound absorption material, which can counteract each other by controlling the surface of the object to produce the opposite phase and equal amplitude sound waves [44].

In general, the non-echo system for active control can only be completed with the aid of piezoelectric sensors. The acoustic reflection can be reduced by using piezoelectric materials to generate excitation waves or by controlling the dynamic impedance matching conditions of the object surface. In order to achieve the best noise reduction effect, the position of piezoelectric sensor on the structure surface should be optimized properly [45-48].
To sum up, piezoelectric sound-absorbing materials can be used alone, or combined with traditional dissipative media. At the same time, shunt circuit or resonance circuit can be connected in series to adjust the sound-absorbing frequency band, and the sound-absorbing frequency band can be widened by stacking layers. The active control system needs piezoelectric detection system and excitation system, and achieves the effect of anechoic stealth by controlling the excitation elements. The disadvantage of this kind of materials is that more piezoelectric elements and circuit devices are needed, which makes it difficult to integrate, and it is more difficult to assemble to underwater equipment than resonance and porous materials.

4. Metamaterials

Metamaterial is a material or multi-component material designed to have supernatural properties. They are made from assemblies of multiple elements fashioned from composite materials such as metals or plastics. Metamaterials derive their properties not from the properties of the base materials, but from their newly designed structures. Metamaterials can realize negative density, negative stiffness, negative refractive index, so it has important applications in focusing imaging, wave control, stealth and so on. The metamaterials available for acoustic path planning are described below.

The gradient medium which controls the sound wave is determined by the microstructure of the local element. The gradual change of refractive index in the spatial distribution is realized by ingenious design of the element geometry and material selection. The gradient refractive index media like a “optical black hole”, which focus incident wave energy to a central absorbing core regardless of the direction of incident. Generally the structure consists of two parts, respectively, shell and core. Because the material parameters in the shell are in a gradient distribution, the propagation waves will bend, and point to the core. The incident energy is absorbed by the damping effect of the core material. Based on this, someone developed air acoustic black hole. Compared with the traditional sound-absorbing materials, this kind of sound-absorbing black hole technology has omni-directivity. No matter what the angle between the wave front and the outer surface of the sound-absorbing equipment is, it can achieve the same sound-absorbing effect [49-55].

The difficulty in the design of acoustic black hole material lies in the refractive index design of shell structure. Generally, it needs to calculate the acoustic reflection and transmission coefficient of microstructure to deduce. The design process is complex, and it needs to combine with dissipation medium to achieve sound absorption. The theory of acoustic cloak is similar to that of acoustic black hole. It can achieve invisibility by planning the propagation path of wave. The difference is that acoustic cloak can achieve perfect invisibility without the participation of dissipative medium. Through the modulation of anisotropic metamaterial, the spatial bending of sound wave can be realized and the diffraction behaviour can be generated around the object.

The acoustic invisibility cloak is also derived from the concept of optical cloak, and its mechanism is the same as the transformation invariance of two-dimensional electromagnetic wave equation. In the case of coordinate transformation, we can get the medium parameters distribution in physical space by a specific mapping between physical space and virtual space. The material parameters in physical space varies in different position, variable continuously and anisotropy. The singular values of the material parameters will appear in an improper transformation. It is difficult to find the material with continuous change in nature. The perfect cloak does not exist, but we can construct a near perfect cloak by combining metamaterial and layered technology. There are three kinds of cloak generally, respectively, IC (inertia cloak), PM (pentamode) cloak and ICPM cloak [56-65]. The bulk modulus of inertia cloak is isotropy, but the density is anisotropy. However the PM cloak is the opposite. The ICPM is anisotropic in density and bulk modulus.

Cummer pioneered the existence of 2D acoustic cloak through analogy optical cloak, and the cloak space presented by him is density anisotropy. Cheng et al. deduced the spatial anisotropic density and isotropic moduli distribution of 3D acoustic cloak through the similarity of acoustic-electric equation. On the basis of predecessors, Norris analysed the theory of cloaks in detail, and obtained the spatial distribution expression of the material parameters of three kinds of cloaks. For PM cloak, he thinks that
honeycomb structure can realize the anisotropy of stiffness. By weakening the connection point, reducing the shear modulus, the anisotropy of stiffness can be modulated by changing the aspect ratio of hexagon of honeycomb structure to meet the requirement of cloak shell. Chen Y et al. implemented Norris' idea and realized the design of broadband PM cloak with the help of cellular structure [66]. For PM cloaks, the selection of characteristic stress vector needs to meet the static equilibrium condition, so the transformation function is limited to cylindrical, spherical or other quasi symmetric mapping.

Density anisotropic materials for IC: laminated materials and vibration inclusions. Laminated materials have weak dispersion effect and can achieve anisotropic density in a wide frequency band, which can be designed by mixing ratio, with short design period and strong feasibility compared with resonant inclusion materials. Torrent et al. and Cheng et al. used this material to design a two-dimensional cylindrical invisibility cloak, two kinds of isotropic media are used instead of one kind of anisotropic media. By discretizing the transformation area of the cloak, the media of each layer that meets the requirements of discretized physical space parameters are distributed in a circular way and arranged radially to fill the whole ring-shaped cloak area. The sound field in the ring-shaped area is squeezed and deformed due to the anisotropy of the material and bypasses the central hole area. Chen H et al. design an acoustic cloak with concentric alternating layered structure with homogeneous isotropic materials on the basis of effective medium theory. When each layer has proper density and bulk modulus, the structure can behave as an effective transformation medium. The cloak possesses low-reflection and power-flow bending properties for different shapes of wave front both in far-and near-fields, which could perfectly approximate the ideal cloak. In addition, the periodic arrangement of solid inclusions in the liquid can also achieve anisotropic density, Pop and Cummer use this material to complete the design of broadband carpet type underwater acoustic invisibility cloak. The working mechanism of resonance material is caused by the elastic difference of elastic element in two principal axes. In addition, shunt circuit structure and board metamaterial can also be used in cloak stealth design [63, 67-68]. The space discrete optimization of the material field of the cloak shell can improve the stealth effect of the imperfect cloak. For the same equipment, the best stealth effect with the ICPM cloak, followed by the PM cloak, and finally the IC [69]. Sun Y et al. studied the anechoic performance and mechanism of underwater elastic sphere shell covered with coating at low frequency, and formulated the analytic expression of scattering sound field from underwater elastic sphere shell covered with multi-layered medium approximated acoustic cloak. They show that inside the multi-layered medium, the direction of transmission is changed, the acoustic field is gradually deflected, and the acoustic energy flux is guided around the target, which reduce the scattering intensity at low frequency, but also the acoustic intensity of target's surface is very weak [70].

Although the above mentioned materials can achieve better stealth effect, but in fact rarely used. In addition to the fact that the material parameters are difficult to be realized, the multilayer structure is usually larger in size, which are contrary to the requirements of low cost and small size. After a lot of research we have some inspiration of metasurface, which may achieve better stealth effect with smaller thickness. It is a kind of single layer material, and can be used to modulate the phase and amplitude of incident wave. Its design idea is steering the acoustic wave by designing the spatial phase gradient structure, such as a labyrinth structure, Helmholtz resonator, and resonance film.

5. Conclusion
Due to the needs of national defines security, there are a large number of researchers engaged in underwater stealth research. There are a variety of specific stealth technology, we can only conclude several of the above. The porous material has the advantages of high frequency sound absorption, easy manufacture and low cost. But we should take into account the strength of the material because of the high hydrostatic pressure. Active control materials have the ability of tunable, as a whole, the configuration of the control system is complicated, and there are some challenges to the underwater application. Resonant materials has a characteristic of narrowband generally. And it's widely used in underwater sound absorption. Cloak is a new technology developed in the last ten years, it has a significant performance in terms of stealth, but difficult to manufacture and its structure is relatively
thick. We hope to have a material, which is relatively thin and has good mechanical properties, to achieve underwater perfect stealth. This requires a breakthrough in mechanism innovation and structural design.

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