Active underwater acoustic control of polymer based piezoelectric composites

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Abstract. Acoustic stealth of the submarine has always been the most valuable research field for Security Department of the Navy over the world. In this paper, the feasibility of underwater anechoic coating with the polymer matrix piezoelectric composite material has been studied. On the basis of the Thomson-Haskell matrix method, we have derived the reflected transform matrix and calculated a semi-analytical solution to the problem by using the MATLAB. It is found that the underwater anechoic effects of this new material are related to the material proportion of each composites, the control voltage, geometric parameters, incident angle and frequency and so on. The studies have showed that: the polymer matrix piezoelectric composite material takes the advantages of both the viscoelastic material and the piezoelectric material and the use of the new material has a superior nature than the traditional materials to the suppression of underwater acoustic reflection.

1. The introduction
Numerical analysis and active control of underwater structural acoustic radiation and transmission are very important for achieving quiet submerged structures. Active noise cancellation [1-5] means that when the sound source is known, the sound wave influence could be offset by emitting the opposite phase sound wave. Bao [6] et al. firstly used piezoelectric materials for underwater noise elimination, and obtained the numerical simulation of acoustic waves perpendicular to the surface of objects through the "average theory", and found that this model has the characteristics of reducing reflected acoustic waves well. Later, Jae-Hwan Kim et al. [7] adopted a method called hybrid numerical simulation to obtain some numerical analysis structures corresponding to the electricity on the steel plate embedded with piezoelectric materials from acoustic waves with different incident angles. Clyde Scandrett [8] has analyzed the underwater sound pressure wave radiation of the spherical composite layer and the underwater noise attenuation properties of several different forms of double-layer plates. The author has obtained the transmission pressure corresponding to sound waves of different frequencies under a given voltage. Some people have also studied noise reduction with different arrangement [9]. Zhao [10-11] used Thomson-Haskell matrix method to study the relationship between incident acoustic pressure, reflected pressure and control voltage of an infinite length elastic/piezoelectric double-layer composite plate.

In this paper, the active noise reduction properties of PZT-4 ceramic powder and PVDF piezoelectric polymer composite are discussed.
2. Theoretical analysis

2.1. Simplification of computational model
When the submarine motioning in the sea, the space is abstracted for a semi-infinite plane of the fluid, hypothesising submarine and fluid coupling vibration eventually embodied in a pressure wave with arbitrary angle (from the pan is vertical to the direction of the incident wave angle) effects on the hull surface. Due to the vibration in the ideal fluid with no shear force, the sound in the fluid medium is represented as a longitudinal wave of pressure wave propagation, which does not decay, and the incident wave is expressed in the form of simple harmonics.

The ship shell is laid as a double-layer plate with external steel and internal pressure, and the two layers are in close contact with each other. The upper surface of the elastic layer is in contact with the liquid environment, and the bottom of the piezoelectric polymer layer is in contact with the atmospheric environment. As shown in Figure 1, it is assumed that the fluid-solid interface is the x axis, the vertical direction of the double-layer plate is the z axis, the vertical coordinate of the bottom of the elastic layer material is \( z_1 \), and the vertical coordinate of the bottom of the piezoelectric composite material is \( z_2 \).

![Simplified schematic diagram](image)

Fig. 1. Simplified schematic diagram

2.2. Propagation of sound
In the piezoelectric composite material layer, the piezoelectric equation matrix of the piezoelectric material \([12]\) is substituted. Combining the electrostatic balance equation and the equilibrium of the element body that the piezoelectric material needs to satisfy in the plane, the combined force satisfies the momentum equation and the controlling equation that the sound propagation displacement and potential potential should satisfy in the piezoelectric composite material is obtained:
\[
\begin{align*}
\frac{\partial^2 u_p}{\partial x^2} + (c_{13} + c_{44}) \frac{\partial^2 w_p}{\partial x \partial z} + c_{44} \frac{\partial^2 u_p}{\partial z^2} + c_{33} \frac{\partial^2 w_p}{\partial z^2} + \rho \frac{\partial^2 u_p}{\partial t^2} &= -(e_{31} + e_{15}) \frac{\partial^2 \phi}{\partial x \partial z} \\
\frac{\partial^2 w_p}{\partial x^2} + (c_{13} + c_{44}) \frac{\partial^2 u_p}{\partial x \partial z} + c_{33} \frac{\partial^2 w_p}{\partial z^2} + \rho \frac{\partial^2 w_p}{\partial t^2} &= -e_{15} \frac{\partial^2 \phi}{\partial x^2} - e_{31} \frac{\partial^2 \phi}{\partial z^2} \\
\frac{\partial^2 w_p}{\partial x^2} + (e_{31} + e_{15}) \frac{\partial^2 u_p}{\partial x \partial z} + c_{33} \frac{\partial^2 w_p}{\partial z^2} &= \varepsilon \frac{\partial^2 \phi}{\partial x^2} + \varepsilon_3 \frac{\partial^2 \phi}{\partial z^2}
\end{align*}
\]

Wherein, \(e_{ij}\) -- the piezoelectric coefficient matrix of piezoelectric composite material;
\(
\varepsilon_i
\) -- the dielectric coefficient matrix of piezoelectric composite materials;
\(c_{ij}\) -- the elastic coefficient matrix of piezoelectric composite material;
\(\rho\) -- densities of the piezoelectric composite material layer;
\(u_p\) -- the horizontal displacement of the piezoelectric composite material layer;
\(w_p\) -- the displacement in the direction of the piezoelectric composite material layer;
\(\phi\) -- potential of external electric field.

In the elastomeric material layer, since there is no piezoelectric effect, there is no corresponding electric displacement and piezoelectric dielectric constant, where is the Lame constant.

2.3. Transfer matrix solution
The Thomson-Haskell\(^{[13]}\) matrix method is used to solve the governing equations of the piezoelectric composite layer. The partial differential equations can be transformed into equivalent ordinary differential equations, and a transfer matrix of order 6 can be obtained. The new value of the variable is obtained by passing the matrix along with the corresponding boundary conditions at the interface. Since there is no piezoelectric effect in the elastic material layer, based on the same principle and the solution method of Thomson-Haskell matrix, the fourth-order transfer matrix of the propagation law of each variable in the elastic material layer is obtained. Let the applied potential at the bottom of the piezoelectric composite material be zero, and the applied potential potential at the interface of the two-phase material be set as \(\phi_0\). In other words, a new fourth-order transfer matrix is obtained for the piezoelectric composite material layer. The transfer relation of the piezoelectric composite material layer is substituted into the expression of the transfer relation of the elastic material layer, and finally the relation between the displacement and stress variables of the upper and lower surfaces of the entire overburden material is obtained. Then, by applying the boundary conditions of the upper and lower surfaces, the expression of the reflected wave pressure can be obtained.

2.4. Programming calculation process
The calculation process can be summarized in Figure 2, and the MATLAB programming can be carried out according to the ideas shown in the figure.
3. Analysis of numerical simulation results

3.1. Material parameters

In this paper, we only discuss the properties of the piezoelectric composites fused by PZT-4 ceramic powder and PVDF piezoelectric polymer. The original data of the materials are referred to the introduction in the literature [14-15] and listed in Table 1,2.

| Parameter types | Typical unit value of magnitude | Unit | Value |
|-----------------|---------------------------------|------|-------|
| PZT-4 PVDF      |                                 |      |       |
| The dielectric constant | $\varepsilon_{11}$, $\varepsilon_{33}$ | relative to the dielectric constant, cardinal number $\varepsilon_0 = 8.85 \times 10^{-12}$ | dimensionless | 1475 | 12.505 |
|                 | $\varepsilon_{33}$              |      | 1300  | 11.986 |
| Piezoelectric constant | $e_{11}$             | 1    | c/m$^2$ | -5.2  | -0.13 |
|                  | $e_{33}$                     |      |       | 15.1  | -0.276 |
|                  | $e_{15}$                     |      |       | 12.7  | -0.135 |
| Elastic constant | $c_{11}$                      | $10^{10}$ | N/m$^2$ | 14.5  | 23.824 |
|                 | $c_{13}$                      |      |       | 6.09  | 0.219 |
|                 | $c_{33}$                      |      |       | 15.9  | 1.064 |
|                 | $c_{44}$                      |      |       | 5.18  | 0.215 |
| Material Name | $\rho$ (kg/m$^3$) | $\lambda$ (10$^{10}$Pa) | $\mu$ (10$^{10}$Pa) |
|---------------|------------------|----------------------|----------------------|
| Steel         | 7700             | 9.7                  | 8.3                  |

In addition, the parameters of water in the flow field are as follows. The density of water is equal to 1000 kg/m$^3$ and the phase velocity is international unit with the order of magnitude 1500.

3.2. Results analysis

3.2.1. Noise reduction law of volume change of piezoelectric ceramic powder
When the volume fraction of the piezoelectric ceramic powder changes from 0% to 70%, it can be seen from Fig. 3 that the amplitude of the control voltage gradually decreases with the increase of the volume fraction of the piezoelectric ceramic powder. When the volume fraction of piezoelectric ceramic powder is 70%, the required voltage is the least, which is also consistent with the conclusion mentioned in reference [16] that the comprehensive performance of piezoelectric ceramic powder is the best when the volume fraction of piezoelectric ceramic powder is 70%.

![Fig. 3 Voltage amplitudes of different volume fractions](image)

3.2.2. Comparison of control voltage with monomer piezoelectric ceramic materials

![Fig. 4 Calculation diagram of control voltage amplitude](image)
In the case of the same material, it is assumed that the control voltage frequency is 1kHz. For the double-layer shell material, the thickness of the elastic material layer is 1cm and the thickness of the piezoelectric composite material layer is 1mm. Fig. 4 shows that in order to eliminate the same incident wave pressure, the maximum control voltage applied to PZT/PVDF piezoelectric composites is much smaller than that of PZT monomer ceramic materials. When the incident wave pressure incident angle is about 16°, it can be seen that the required control voltage is the least, which is almost 0. The characteristics of piezoelectric materials have a high performance on the active noise reduction. The maximum value of the control voltage occurs at different positions of the two materials, and the phase of the control voltage is also required. It can be seen from the above numerical simulation that the noise reduction effect of PZT/PVDF piezoelectric composite material is better than that of monomer piezoelectric ceramics. This new type of material has better noise reduction performance, which provides a strong support for the following studying on the influence factors of noise reduction in the future.

3.2.3. Analysis of influence factors of noise reduction

(1) Thickness increase of elastic layer
This paper discusses the change rule of elastic layer thickness from 3cm to 5cm. It can be concluded from Fig. 5 and Fig. 6 that the required amplitude of control voltage decreases with the increase of elastic layer thickness in order to achieve the same muffling effect. It conforms to the rule that the dissipation effect becomes better with the increase of the elastic layer thickness under the same other conditions. Within a certain range of incident angle, the noise reduction can be achieved by the piezoelectric coupling effect of the material layer. The position of the maximum value of the control voltage is gradually stable at a small position of the incident angle with the change of the thickness. The variation of amplitude and angle increases with the increase of thickness, but decreases with the change of angle of incident wave.

![Fig. 5 Voltage Angle Diagram of Elastic Layer Thickness Variation](image-url)
(2) Thickness variation of piezoelectric layer

With the thickness of piezoelectric composite materials varying from 1mm, 3mm and 6mm respectively, it can be observed more clearly in Figure 7 and 8 that the piezoelectric coupling effect of the composite material changes with the increase of incident wave pressure Angle, suggesting that there will be a relatively optimal value within a certain thickness range of the piezoelectric composite material. In the vicinity of 16°, the control voltage is almost zero. Similarly, within the incident angle range of the incident wave pressure after 45°, the amplitude of the required control voltage is also quite small, which is of great significance to the acoustic stealth of the shell material itself. However, the position where the control voltage reaches its maximum value also deviates to a large angle with the increase of the thickness, which is different from the variation law of the elastic layer. As a whole, the amplitude and angle of the control voltage decreases gradually with the increase of the incident angle of the incident wave, which means that the phase difference between the control voltage and the incident wave also decreases. When the incident wave pressure is almost horizontal, the amplitude angle of the control voltage is almost zero. This is similar to the change law of the elastic layer. It can also be seen from the figure that the amplitude and angle of the control voltage increases with the increase of the thickness of the piezoelectric composite material layer.
(3) Influence of frequency change of incident wave

In fact, the frequency of incident wave varies. When the incident frequency of incident wave is 1kHz, 5kHz, 50kHz and 100kHz respectively, assuming that the thickness of elastic layer is 1cm and that of piezoelectric composite material layer is 1mm, the amplitude of control voltage required to be applied when the incident wave is incident from different angles is obtained as shown in Figure 9:

![Voltage Amplitude Diagram of Frequency Variation of Incident Wave](image)

In order to eliminate the influence of wave pressure at different frequencies, when the incidence is greater than 50°, the effective noise reduction can be achieved by a specific coupling layer material. As the frequency of the incident wave increases, the amplitude of the control voltage applied decreases. And the magnitude changes very quickly. With the increase of frequency of incident wave, the phase difference between incident wave and control voltage increases with the increase of
frequency. On the other hand, the variation law of the amplitude and angle of the control voltage presents an overall decreasing trend as the incident angle of the incident wave changes from almost vertical interface incident to almost horizontal incident in the low frequency stage, and decreases to almost 0. In the high frequency stage, there is no regular decreasing law.

| Incident frequency | 1KHz       | 5KHz       | 50KHz      | 100KHz     |
|--------------------|------------|------------|------------|------------|
| Voltage amplitude  | 332.8069+114.1996i | 13.3215+2.8823i | 0.1495+2.9289i | -0.0395-3.0379i |
| Amplitude Angle    | 9.1°       | 9.1°       | 9.1°       | 9.1°       |
| Voltage Angle      | 18.939°    | 59.796°    | 87.078°    | 89.254°    |

Table 3 shows the variation rules of the amplitude and angle of the control voltage applied when the incident wave is incident from different angles, indicating that the established model is more suitable for the incident wave with low frequency. In fact, because the high-frequency sound wave vibrates very fast, there will be a rapid energy exchange in the viscoelastic material medium, which will lead to the rapid attenuation of energy and the rapid reduction of sound wave. The piezoelectric composites have both viscoelastic and piezoelectric properties, and this excellent coupling performance is beyond the reach of traditional piezoelectric materials. This is why no artificial control voltage or very little control voltage is required in the piezoelectric composite material layer when the high-frequency sound wave occurs.

4. Conclusion and prospect

By adding an appropriate voltage to the piezoelectric composite material layer, the pressure of the incident wave in a certain direction can be eliminated and the purpose of noise reduction can be achieved. The elimination of a given incident wave pressure is related to the properties of the applied control voltage, the frequency of the incident wave pressure, the incident angle, the thickness of the shell material layer, including the volume fraction of each component in the shell material, etc. Some numerical simulation results are given in this paper on the noise reduction of a double-layer plate which is in a piezoelectric composite material and elastic material and with plane incident sound waves. In practice there could be incident wave transmission in the material too, this also needs to be considered in the next study as well as the spherical shell model that actual curvature of submarine shell type is. However, there are still some conclusions for reference in this paper.

1) Compared with monomer piezoelectric ceramic materials, the noise reduction effect of the new piezoelectric composite material is quite excellent. The double-layer infinite plate-like structure composed of piezoelectric composite material and elastic layer can be used to eliminate sound by applying appropriate control voltage on the piezoelectric composite material layer. And within a certain range of incident angle variation, no or very little control voltage can be applied, but through the piezoelectric effect of the piezoelectric composite layer itself and the dissipation of the elastic material layer, the effect of noise reduction can be achieved.

2) For incident sound waves of different frequencies, especially in the low frequency stage, the amplitude of control voltage tends to decrease with the increase of incident wave frequency, while the amplitude of control voltage also decreases with the increase of incident angle. However, for incident sound waves with the same incident angle, the phase difference between the incident wave of high frequency and the control voltage is smaller than that of the incident wave of low frequency.

3) When the thickness of the double-layer material of the shell changes, under the same conditions, the amplitude of the required control voltage decreases as the thickness of the elastic layer increases, which is related to the dissipation effect of the elastic material. With other conditions being the same, the control voltage required decreases with the increase of the thickness of the piezoelectric composite. In addition, the variation of the control voltage amplitude angle also conforms to the law of decreasing with the increase of the incident angle of the incident wave. The phase difference between
the control voltage and the incident acoustic wave decreases with the increase of thickness.  
(4) This paper also discusses the control voltage requirements of the new piezoelectric composites with different volume fractions of piezoelectric ceramic monomers. The noise reduction performance of piezoelectric composite is better than that of monomer piezoelectric ceramic, and the optimal volume fraction of piezoelectric composite is verified.

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