Design simulation and analysis of deep-sea transducer

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Abstract—Aiming at the design limitations of current deep-sea transducers, this paper designs and manufactures a deep-sea transducer based on the theoretical analysis of the characteristics of the piezo ring. This transducer is potted and vulcanized into a solid structure with sound-permeable rubber. As a result, not only the deep water pressure resistance is achieved, but also the operating frequency range is broadened by the high-low order coupling vibration between the piezo ring and the sound-permeable rubber. The influences of the main parameters on the electroacoustic characteristics of the transducer are analyzed in detail by FEM. Prototypes are developed subsequently. The measured results show that the simulation and measured results have high consistency. The maximum working depth of the transducer can reach 10000 m, and the beam direction is omnidirectional in the upper hemisphere. In the frequency range of 7~20 kHz, the transmitter voltage response is higher than 120dB, and the receiver sensitivity is greater than -200dB. This research indicates that the transducer has excellent deep-water characteristic and transmit-receive performance.

1. INTRODUCTION
The deep sea is rich in resources and has unlimited potential. Deep-sea exploration, research and development are currently a hot area of competition among countries. As a key component of underwater acoustic communication, detection and navigation systems, deep-sea transducers are bound to be vigorously developed. Considering the balance between detection range and detection accuracy, there is an urgent need for deep-sea transducers in the middle and low frequency bands [1].

How to ensure the stable performance of the transducer under high hydrostatic pressure through effective structure or reasonable design is the first technical problem to be solved by the transducer working in deep sea conditions. The current solutions generally include pressure relief mechanism, pressure compensation mechanism, oil-filled structure, and overflow structure [2-4]. Among them, oil-filled and overflow structures are the most popular. However, the above two types of pressure resistance put forward certain requirements on the structure of the transducer. Therefore, it is necessary to find new solutions for transducers outside the requirements, such as a closed potting structure. This
paper designs a deep-sea transducer based on the theoretical analysis of piezo ring characteristics. In order to achieve deep water pressure resistance, the transducer is potted and vulcanized into a solid structure with sound-permeable rubber, and then the high-low order coupling vibration between the piezo ring and the sound-permeable rubber is used to broaden the operating frequency range. The influences of the main parameters on the electroacoustic characteristics of the transducer are analyzed in detail by FEM. Prototypes are developed subsequently. The measured results show that the simulation and measured results have high consistency. The maximum working depth of the transducer can reach 10000 m, and the beam direction is omnidirectional in the upper hemisphere. In the 7~20 kHz frequency range, the transmitter voltage response is higher than 120dB, and the receiver sensitivity is greater than -200dB. This research proves that the transducer has excellent deep-water characteristic and transmit-receive performance. Thus, it has broad application prospects in the field of underwater acoustic communication.

2. TRANSDUCER DESIGN AND SIMULATION

2.1. Theoretical Basis

The piezo ring transducer mainly works in the basic breathing mode of the torus, which is the first-order radial vibration mode [5]. Compared with transducers of other shapes, it has the advantages of simple structure, stable performance, non-directivity in the horizontal direction and excellent deep-water characteristics [6]. So, it is the first choice for deep-sea transducer design.

The design of deep-sea transducers involves theoretical calculations of electro-acoustic parameters and water pressure resistance capability. The resonance frequency is the most basic electrical performance parameter of the transducer. Generally, the first-order radial resonance frequency of a thin ring is given by [7].

\[ f_r = \frac{1}{2\pi} \sqrt{\frac{1}{\rho S_{11}^e}} \]

Where \( \bar{r} \) is mean radius of the piezo ring, \( \rho \) and \( S_{11}^e \) are density and compliance constant of the piezo ring.

Receiver sensitivity (receiver voltage response, RVS) is also one of the most important electroacoustic indicators of the transducer. For a ring transducer with a cap on the tube end, the receiver sensitivity is as in [7]

\[ M = r_2 \left( g_{33} \cdot \frac{t}{r_2} + g_{31} \cdot \frac{3-t}{2t} \right) \]

Where \( r_2 \) and \( t \) are outer radius and wall thickness of the piezo ring, \( g_{33} \) and \( g_{31} \) are piezoelectric constants.

The high hydrostatic pressure in the deep sea will cause the piezo ring to produce circumferential elastic and plastic deformation, destroy the mechanical structure, and cause functional failure. Therefore, the pressure resistance characteristics of the piezo ring are critical. According to the material strength theory, the allowable external pressure is as below [4]

\[ p = KE \left( \frac{t}{2r_2} \right)^m \]

Which \( r_2 \) and \( t \) are outer radius and wall thickness of the piezo ring, \( E \) is elastic modulus, \( K \) is ring characteristic coefficient, usually 2.2, \( m \) is safety coefficient, usually 3.

2.2. Design Ideas

According to the (2) and (3), it can be seen that if the pressure resistance of the ceramic ring is to be improved (increase \( t \), reduce \( r_2 \)), part of the receiver sensitivity will be sacrificed. This is obviously not in line with the original design intention. In addition, the single radial vibration mode of the ceramic ring also limits the working bandwidth of the transducer. Therefore, the structural design of the deep-sea
transducer is a solid structure that uses sound-permeable rubber as an integral potting and vulcanization, which mainly includes three parts: tail mass, piezo ring and sound-permeable rubber, as shown in Fig. 1. Theoretically, the application depth of the transducer will not be limited by and because of the solid structure which the internal and external pressures can always maintain balance. At the same time, the receiver sensitivity can be flexibly guaranteed. When the piezo ring undergoes high-order radial vibration under the excitation of an electric field, it will drive the surrounding sound-permeable rubber to produce low-order axial resonance, thereby forming a high-low-order mode coupling hump effect. By optimizing and adjusting the coupling strength of the two-order modes, the working frequency band of the transducer can be broadened. Meanwhile, the radiated sound field formed by the coupling vibration between the piezo ring and the sound-permeable rubber will use the unidirectional baffle effect of the tail mass to form the omnidirectional hemispheric directivity of the transducer.

![Figure 1 Schematic diagram of transducer section](image)

2.3. **Piezo Ring Simulation and Analysis**

Through theoretical calculations and engineering requirements, it is determined that the average radius of the PZT-4 piezoelectric ceramic ring with radial polarization is 40mm. As shown in Fig. 2, a finite element model of the entire piezo ring is established to more intuitively observe the radial breathing vibration mode of the piezo ring, the first-order radial vibration mode and admittance frequency response characteristic are obtained by FEA.

![Finite element model](image)

(a) Finite element model

![First-order mode shape](image)

(b) First-order mode shape
It is noted that the first-order vibration mode of the piezo ring is shown as a breathing motion that expands uniformly along the radial direction. The first-order radial resonance frequency of the piezo ring is about 13.2 kHz. The simulation result is consistent with the calculation of (1).

2.4. Numerical Simulation and Analysis of Transducer

Considering that the transducer is an axisymmetric structure, only a 1/4 part of the fluid finite element model is established, as shown in Fig. 3; ignoring the structure details such as electrodes and coupling agents that have little influence; fluid domain radius setting 0.6m, which satisfies the fluctuation conditions and far-field conditions.

Through numerical simulation analysis, the changes of the main electroacoustic parameters of the transducer with the structural parameters (h1, h2, and h3) are studied. The frequency response changes in the transmitter voltage response and receiver sensitivity of the transducer with each structural parameter are shown in Fig. 4 and Fig. 5, respectively.

(c) Admittance frequency response curve

Figure.2 Simulation results of the piezo ring

Figure.3 1/4 part FEA model of the transducer in the fluid domain

(a) The TVR varies with h1
Figure 4. Transmitter voltage frequency response curve

(b) The TVR varies with h2

(c) The TVR varies with h3

(a) The RVS varies with h1

(b) The RVS varies with h2
It can be seen from the FEA results that the change of the parameter $h_2$ has no obvious influence on the transmitter voltage response and receiver sensitivity of the transducer, so the watertight characteristic should be paid attention to in the engineering design. The parameter $h_1$ has little effect on the transducer's transmitter voltage response, but in the 11-20 kHz frequency range, the receiver sensitivity of the transducer tends to gradually increase as the parameter $h_1$ thickens. Therefore, $h_1$ can be changed in the engineering design to adjust the receiver sensitivity of the transducer in the above frequency range. The influence of parameter $h_3$ on the transducer is mainly reflected in the 9-16 kHz frequency range, and with the substantial increase of parameter $h_3$ (compared to the change range of $h_1$ and $h_2$), both the transmitter voltage response and receiver sensitivity tend to rise. In the specific engineering implementation, the relationship between the electrical performance gain brought by the increase of $h_3$ and the overall structural requirements should be weighed.

3. Prototype Production and Testing

Based on the FEA results, combined with the needs of engineering applications, the size parameters of the transducer elements and other structural parts are determined. The production process is divided into three steps: firstly, the components are pre-treated; secondly, the components are assembled; finally, the sound-permeable rubber is used for potting and vulcanization. The completed transducer prototype is shown in Fig. 6. In addition, the test results of the main electroacoustic performance parameters of the transducer prototype are shown in Fig. 7.
It can be observed from Fig. 7 that the transducer effectively realizes the high-low-order modal coupling between the piezoelectric ring and the sound-permeable rubber in the middle and low frequency bands, which broadens the operating frequency range. Furthermore, the simulation and test results can maintain high consistency, which verifies the rationality of the simulation parameter settings. The test results show that the transmitter voltage response is higher than 120dB and the receiver sensitivity exceeds -200dB in the 7-20 kHz frequency band, which indicate good transmit-receive performance. Moreover, the prototype has obvious omnidirectional pointing characteristics in the upper hemisphere. In addition, the transducer prototype has also passed the test verification under 100MPa simulated water pressure environment.
4. CONCLUSION
Based on the results and discussions presented above, the conclusions are obtained as below:

Based on the theoretical analysis of the resonant frequency, receiver sensitivity and pressure resistance characteristics of the piezo ring, the design plan are determined: the sound-permeable rubber is used to potting and vulcanizing the entire transducer into a solid structure, which not only realizes deep water pressure resistance, but also broadens the working frequency range by the high-low-order coupling vibration between the piezo ring and the sound-permeable rubber.

The influences of the main parameters on the electroacoustic characteristics of the transducer are analyzed in detail by FEM, so as to provide guidance basis for engineering design.

A prototype was made and its performance parameters were tested. The results show that the simulation and test results have high consistency, the transducer has excellent deep-water characteristic and transmit-receive performance.

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