Design of an underwater acoustic array for full ocean depth multi-beam echo sounder

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Abstract. In order to meet the technical requirements of full ocean depth multibeam echo sounder, the underwater acoustic array must have the ability of wide coverage, broadband response, high sensitivity and high reliability. This paper presents a design of underwater acoustic array based on Mills cross configuration with separate transmitting and receiving units. The arrays have modules design, hence the beamwidth of the array can be adjusted according to particular installation requirements. The working frequency band of the arrays is between 10.5kHz to 13.5kHz, and the coverage angle can cover $-71.6^{\circ} \sim 71.6^{\circ}$. The Integrated design is used to achieve a wide-angle beam coverage of the planar array, which combines the transducer and the sound baffle together to realize a wide directivity of the array elements. The longitudinal bending transducers are designed to meet the broadband requirements for the transmitting array, which are Tonpilz transducers with flexural radiating head. On the other hand, each element of the receiving array is composed of several hydrophones, which are connected in series to achieve high sensitivity. The double-layer watertight technology is also applied in our design, ensuring stable performance and long service life.

1 Introduction

Multibeam echo sounder, improved by the single beam echo sounder, can get hundreds or even thousands of sound intensity sample data within the measurement section, thus can implement full coverage measurement in the area. The maximum detection depth of different types of multibeam echo sounder ranges from 100 meters to 11,000 meters, among them, the technology of the full ocean depth multibeam echo sounder is the most complicated and the scale of it is the largest.

In order to meet the technical requirements of the full ocean depth multi-beam echo sonar, the underwater acoustic array must have the ability of wide coverage, broadband, high sensitivity and high reliability. Considering the need for detection range and accuracy, the center frequency of the acoustic array is set to 12kHz with a bandwidth of 3kHz.

This paper presents the design of an underwater acoustic array, which uses the Mills cross configuration with separate transmitting and receiving units. The arrays have modules design, hence the beamwidth of the array can be adjusted according to particular installation requirements.

2 Echo sounder with wide directivity

Multibeam echo sounders prefer wide directivity to provide good coverage of their detection area. In this work, we mainly focus on developing planar acoustic arrays with wide directivity, which are usually used in

large scale multibeam echo sounder systems. However, it should be noted that, due to wave diffraction limit, it is a challenge to achieve wide directivity for acoustic arrays with large aperture size. For example, the directional beam width of the typical Tonpilz transducer is usually less than 90 degrees, and the situation will get worse when transducers forms a plane array with much larger size as compared with a single element. The situation is the same for the receiver arrays, which have narrow beam width even if its single hydrophone element usually has a wide directivity. To overcome the above problem, one could combine transducers with sound baffle to achieve wider directivity.

Fig. 1. The sound field of hydrophone before the baffle.

As shown in Figure 1, assuming the hydrophone "A" is placed before the infinite planar baffle, and the size of A is far less than the wavelength of sound waves in water. The distance between the hydrophone and the baffle is "d", the angle between the incident plane wave and the baffle normal line is " θ ". From the ray acoustics and virtual source method, the response and directivity of

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hydrophones will be affected by the direct wave and the reflected wave caused by the baffle.

Fig. 2. Directivity diagram of different distances. (The real line is the measured value and the dotted line is the calculated value)

According to the virtual source method, the baffle's reflection effect is equivalent to one virtual sound source on the other side of the barrier, which is a mirror of the hydrophone "A". Its amplitude is equal to the amplitude of the incident wave multiplied by the reflection

coefficient of the baffle. The total sound pressure received by the hydrophone in "A" point is equal to the sum of the incident wave and the imaginary source.

Let the amplitude of incident wave be P_0 , and the phase of it be φ . Let the amplitude of reflection coefficient be V_0 . Take the midpoint between A and A' as the reference point of calculation, the total sound pressure is

$$P = P_0 \exp(-jkd \cos \theta) + V P_0 \exp(jkd \cos \theta) \quad (1)$$

$$= |P| \exp(j\phi)$$

Among them

$$|P| = P_0 \sqrt{1 + V_0^2 + 2V_0 \cos(2kd \cos \theta + \varphi)}$$

$$\phi = \varphi / 2 + \tan^{-1} \left[\frac{(V_0 - 1) \sin(kd \cos \theta + \varphi / 2)}{(V_0 + 1) \cos(kd \cos \theta + \varphi / 2)} \right]$$

From the above equation, it is evident that there are several factors influencing the sound pressure received by the hydrophone, including sound frequency, hydrophone-baffle distance, the amplitude and phase of reflection waves. Since the complex reflectance coefficient of the baffle is affected by its thickness, speed and density, the directivity of the array elements can be engineered by changing the hydrophone-baffle distance, baffle's size and its characteristic impedance.

The actual test is in good agreement with the theoretical calculation, for example, at the frequency of 12kHz, as the distance between the hydrophone and the baffle increases (from 19mm to 39mm), its directivity keeps broadening until a concave valley appears in the direction of 0 degrees. The directivity diagram of different distances is as follows. (linear coordinates)

3 The design of transmitting modules

Fig. 3. Comparison between staggered array and equispaced array.

Fig. 4. The transmitting array and modules.

A transmitting module consists of 12 transducers, 72 modules are arranged along the direction of the keel to form a complete transmitting array. The elements are arranged in staggered fashion, thus the aperture of the matrix can be enlarged to obtain larger array gain compared with equispaced arrangement.

The longitudinal bending broadband transducers are designed to meet the broadband requirements of the transmitting array, which are Tonpilz transducer with a flexural radiating head. There are two vibration modes involved in the working frequency band of such transducers. One is the longitudinal vibration mode of the transducer and the other is the bending vibration mode of the radiating head of the transducer.

Fig. 5. The two vibration modes.

By changing the size of the radiating head and the piezoelectric ceramic elements, the frequency and amplitude of the two vibration modes can be adjusted, so as to obtain the broadband effect.

Fig. 6. Effect of changing the radius of radiating head on conductance and TVR.

As shown in figure 6, with the increase of radiating head's radius, the amplitude of longitudinal vibration mode decreases, the amplitude of bending vibration mode increases, and the frequency of both modes decreases. At the same time, with the increase of radiating head's radius, the distance between the two resonance peaks becomes closer, and the bandwidth of transmitting voltage response becomes narrower.

Fig. 7. The influences of changing the height of radiating head on conductance and TVR.

As shown in figure 7, with the increase of radiating head's thickness, the frequency of longitudinal vibration mode remains basically unchanged and the amplitude increases; the frequency of bending vibration mode increases and the amplitude decreases. At the same time, with the increase of radiating head's thickness, the distance between the two resonance peaks becomes further apart, and the bandwidth of transmitting voltage response becomes wider.

Fig. 8. Comparison between the measured performance and simulation.

From the above analysis, it can be seen that the size of radiating head can greatly influence the performance

of the transducer, especially the frequency of the bending vibration mode. The performance of the transducer is also affected by the size of the piezoelectric ceramic stacks, material and size of other structural parts. It is necessary to optimize the design of each component according to actual requirements. The comparison between the measured performance and the simulation of the transducer is as follows.

The directed graph of transmitting module is tested and compared with the calculated value. which the phase angle is set to 0° , 30° , 60° , 75° .

Fig. 9. Comparison between the measured performance and simulation.

It can be seen that the transmitting array can realize beam deflection from 0 to 75 degrees, and can meet the system's wide coverage and broadband requirements.

4 The design of receiving modules

A receiving module consists of 8 elements; the space between each element is 0.45λ . A total of 8 modules are arranged along the direction of perpendicular to the keel of the ship to form a complete receiving array. For each element, it consists of six hydrophones spaced at 0.45λ , every two of them are connected in series to get high sensitivity.

Fig. 10. The receiving array and modules.

All 48 hydrophones in module are fixed on the junction box with high precision, and the electrical connection of the hydrophones is realized inside the junction box. At the same time, the antisound baffle is laid on the surface of the junction box to widen the directivity of the hydrophone element.

The junction box plays the multiple roles of high precision positioning, electrical connection and fixing baffle. After the installation and connection of the hydrophones, the whole polyurethane injection molding is completed on the outside of the junction box. The highly integrated design enables the size of the receiving module to be controlled within an acceptable range.

The sensitivity test results of 8 elements of one module are as follows, indicating that each element has a high consistency.

Fig. 11. Receiving sensitivity of the receiving module.

5 Full array design and installation

As illustrated in Fig.12, the transmitting array and receiving array are installed at the bottom of the ship in a Mills cross configuration. The beam width of the transmitting array is narrow along the keel of the ship, and the beam width of the receiving array is narrow in the direction perpendicular to it. As shown in Fig.12, the transmitting beam and receiving beam overlap to form high-resolution beam footprints, so that the system can have high resolution imaging.

Fig. 12. Working principle of the multibeam echo sound with Mills cross configuration.

Fig. 13. Installing the base frame.

Fig. 14. Installing the modules.

According to the beam width formula of typical line array, the beam width of transmitting array is less than 1

degree, and the beam width of receiving array is less than 2 degree.

$$\theta_{-3dB} = 2 \arcsin(0.443\lambda / L) \quad (2)$$

First, the bottom of the experimental ship is grooved and the base frame is installed.

The modules are then loaded into the base frame one by one; the cables are converged and piped into the cabin.

Finally, apply anti-fouling paint on the modules' surface to complete the whole installation.

Fig. 15. The whole picture of the array.

6 Conclusions

Finally, the underwater acoustic array (1 and 2 degrees beamwidths respectively for transmitting and receiving) has been shipped for seven years. The modules have very high reliability and maintained a good working condition. This is due to double watertight design of the module, which means each component of the module is individually encapsulated, and the whole module is also encapsulated after all the components are integrated together. The transducers and hydrophones both have stable performance and less fluctuation response in working frequency band. By using the anti-sound baffle, the directivity of the elements on the array can be broadened more than 50%. It has good performance in wide-angle beam deflection and can meet the multi-beam echo sounder's requirements.

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