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An Underwater Acoustic Vector Sensor with High Sensitivity and Broad Band

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Abstract: Recently, acoustic vector sensor that use accelerators as sensing elements are widely used in underwater acoustic engineering, but the sensitivity of which at low frequency band is usually lower than -220 dB. In this paper, using a piezoelectric trilaminar optimized low frequency sensing element, we designed a high sensitivity internal placed ICP piezoelectric accelerometer as sensing element. Through structure optimization, we made a high sensitivity, broadband, small scale vector sensor. The working band is 10-2000 Hz, sound pressure sensitivity is -185 dB (at 100 Hz), outer diameter is 42 mm, length is 80 mm. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Broadband, High sensitivity, Small-scale, Acoustic vector sensor.

1. Introduction

Acoustic vector sensors are the hot topics in underwater acoustic detection field both at home and abroad. Acoustic vector sensors can be used to measure the sound pressure in underwater acoustic sound field, and also can get the particle velocity or acceleration at one point in the underwater sound field at the same time [1], thus provide more information and methods for underwater acoustic propagation law study, underwater acoustic sound field distribution character study, and underwater acoustic detection system and instruments study.

With the development of acoustic vector sensor application, especially for the huge advantage in the application of underwater low frequency detection makes users eagerly demand for acoustic vector sensor. Nowadays, acoustic vector sensor that uses accelerator as sensing element are widely used in underwater acoustic engineering [2-8], the low frequency limit of their working band can be less than 100 Hz, but the sensitivity at low frequency is always lower than -220 dB, which cannot meet the long distance detection need, so their effective working band should be higher than 100 Hz. With the frequency of underwater acoustic detection becoming lower, vector sensors with broad band (10-1000 Hz), or low frequency band (1-10 Hz), high sensitivity, and small scale are needed for more and more engineering projects.

In this paper, considering the working frequency, sensitivity and structure parameter of the vector sensor, we designed a high sensitivity accelerometer ICP built-in with its acceleration sensitivity being 800 mV/ms^{-2}, and then we made a broad working band, high sensitivity, small scale vector sensor using the accelerometer as the main sensing element. The parameters of the sensor are: working band

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10-2000 Hz, sound sensitivity -185 dB (at 100 Hz), outer diameter 42 mm, length 80 mm.

2. The Basic Design Theory of Acoustic Vector Sensor

Currently, there are two kinds of acoustic vector sensor: co-vibration vector sensor based on accelerometer, and differential pressure vector hydrophone based on sound pressure hydrophone. The first one is widely used in engineering applications because of its better low frequency acoustic character.

The design theory of co-vibration cylinder vector sensor is that [9] when the geometry size of the rigid cylinder is far less than sound wave length, which means ka<<1 (in which k is the wave number; a is the maximum size of the cylinder), the cylinder will move freely along with sound wave. So, between the vibration amplitude and phase of acoustic rigid cylinder and water particles in the geometric center of cylinder, the relation is that:

$$\left|\frac{v}{v_0}\right| = \frac{2\rho_0}{\bar{\rho}+\rho_0}, \qquad \Delta\phi \to 0 \tag{1}$$

where v is the velocity of the rigid cylinder, v_0 is the particle velocity at the geometric center of the cylinder in the water, $\bar{\rho}$ is the average density of the rigid cylinder, and ρ_0 is the density of the water medium.

From equation (1) we can see that when the average density of the rigid cylinder equals to the density of the water medium, the velocity of the rigid cylinder will equal to the particle velocity at the geometric center of the cylinder in the water, and the phase difference will tend to be zero. So when we design a vector sensor with its working frequency band being 10-2000 Hz, according to its upper limit frequency, the maximum size of the cylinder should meet the equation below:

$$L << \lambda/6 = \frac{0.75}{6} = 0.125m$$

In ideal condition, 1/10 should be the far less requirement, and then the maximum size of the co-vibration cylinder vector sensor should be 1-2 cm.

To meet the requirements above, the built-in accelerometer should be small enough and light enough, but small volume makes its working frequency very high and its sensitivity very low, so it is impossible to design a broad band, high sensitivity, small scale acoustic vector sensor by using a traditional accelerometer. Therefore, in this paper we designed a small scale, light, low frequency high sensitivity accelerometer based on the piezoelectric trilaminar optimized design, and applied to under water acoustic vector sensor design.

According to Equation (1), by the premise of guarantee the technical index (sensitivity, phase) of the acoustic vector sensor, we can slightly broaden the density requirements for the acoustic vector sensor, and then broaden the structure size of it, and finally make the requirement of broad working band and high sensitivity for acoustic vector sensor possible.

Fig. 1 shows the relationship between the velocity of the co-vibration cylinder acoustic vector sensor and the velocity of the particle. Fig. 2 shows the relationship between their phases. From the figures we can see that to ensure the ratio between the velocity of the co-vibration cylinder acoustic vector sensor and the velocity of the particle less than 2 dB and their phase difference less than ±1 degree, the relationship between the average density of the cylinder vector sensor and the density of the water medium should be $0.6 \le \bar{\rho}/\rho_0 \le 1.2$. Thus we can choose a proper average density in a certain range, and realized the enlargement of the sensor wave size.

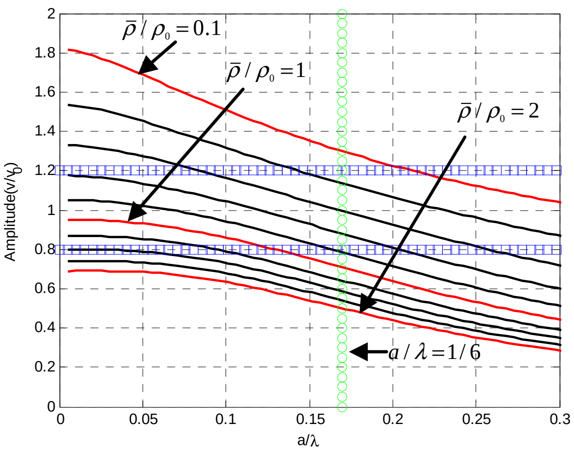


Fig. 1. The character curve of velocity ratio of the cylindrical vector sensor.

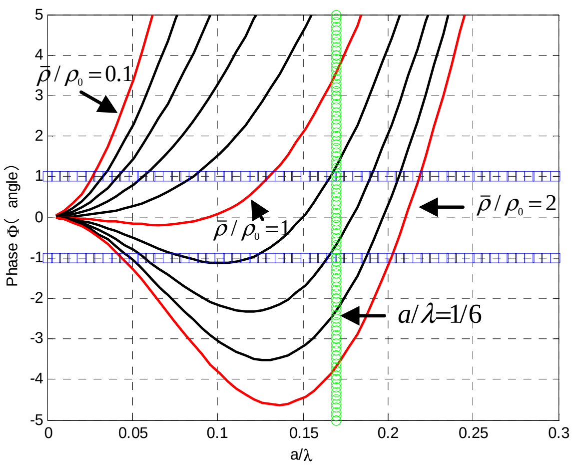


Fig. 2. The character curve of phase of the cylindrical vector sensor.

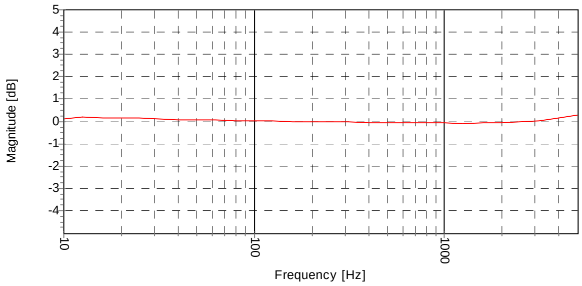
3. The Structure Design of the Acoustic Vector Sensor

3.1. The Design of the Piezoelectric Accelerometer

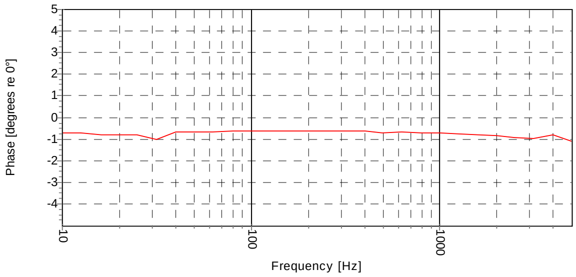
Currently, most of the co-vibration vector sensors use piezoelectric accelerometers as the vibrator to get the vector information in water. Therefore, the performance of the piezoelectric accelerometer will directly influence the co-vibration vector sensor's performance. Both bilaminar piezoelectric and trilaminar piezoelectric are commonly used sensing element [10-12], the natural resonant frequency of piezoelectric accelerometers based on bilaminar piezoelectric and trilaminar piezoelectric can be thousands hertz, therefore their working frequency bands are broad, but their sensitivity are relatively low, most of them are hundreds millivolt per acceleration of gravity. With the development of modern material science, there are more choices for the sensing element of the piezoelectric accelerometer than before, so there are large improvements in increase the sensitivity of the piezoelectric accelerometer that using bilaminar piezoelectric and trilaminar piezoelectric as the sensing element.

Based on the working theory of the trilaminar piezoelectric accelerometer, in this paper we use new type piezoelectric crystal material and built-in ICP circuit, turned traditional high impedance charge output accelerometer into low impedance voltage output accelerometer. Material object after package is showed on Fig. 3, the parameters of it are: outer diameter 20 mm, height 20 mm, mass 32 g. We also calibrated the sensitivity and phase of the accelerometer with B&K 3629 type vibration and shock system, the result of it is showed in Fig. 4.

Fig. 3. The designed accelerometer.



(a) Fluctuation curve of the accelerometer sensitivity



(b) Fluctuation curve of the accelerometer phase

Fig. 4. The testing result of the vector sensor.

The sensitivity of the accelerometer at 160 Hz is 800 mv/ms^{-2}. From the measurement result we can see that in 10-400 Hz, sensitivity fluctuation is less than ±1 dB, phase fluctuation is less than ±1 degree, which met the requirement of design.

3.2. The Design of Co-vibration Acoustic Vector Sensor

To guarantee the design requirements of density for co-vibration vector sensor, we use low density composite material to encapsulate the accelerometer, and make it a cylindrical vector sensor. The size parameters of it are: outer diameter 20 mm, height 45 mm, density is about 1.1 g/cm^3. To decrease the influence of the flow noise and the elastic element installation [1], the co-vibration vector sensor designed in this paper is connected with the shell through elastic element, and the structure diagram of it is showed on Fig. 5.

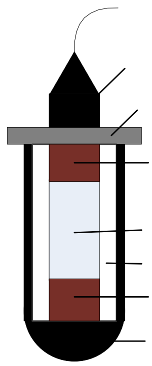


Fig. 5. The structure diagram of acoustic vector sensor.

Finally the shell is encapsulated by polyurethane material, and the material object is showed on Fig. 6. The size of the acoustic vector sensor is ϕ 43×128 mm.

Fig. 6. The acoustic vector sensor.

4. The Measurement Result of the Acoustic Vector Sensor

Under laboratory condition, we have used vector sensor calibration instruments to calibrate the sensitivity of the designed acoustic vector sensor. In 10-400 Hz, we use standing wave tube absolute calibration method, and in 400-2000 Hz, we use comparison calibration method, Fig. 7 shows the sensitivity of the acoustic vector sensor.

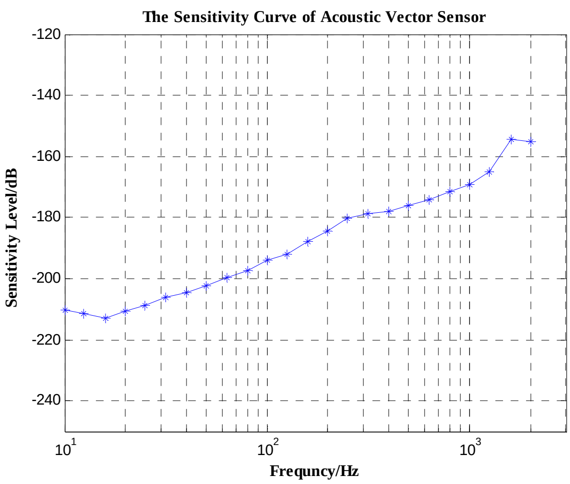


Fig. 7. The curve of the acoustic vector sensor sensitivity.

From the Fig. 7 we can see that the whole performance of the acoustic vector sensor is good, the sensitivity curve under 800 Hz is basically a straight line, which is accord with the changing law of the sensitivity, and the sensitivity of the acoustic vector sensor at 100 Hz is -185 dB (0 dB ref 1V/µPa). In low frequency band (10-400 Hz), using standing wave tube absolute calibration method can effectively eliminate the measurement error caused by low frequency band standing wave tube sound field uncertainty. Beyond 1000 Hz, the sensitivity becomes unstable, the reason maybe because the sensitivity of the acoustic vector sensor is too high, and the vibration interference caused by the measurement system and the external environment is strong, but the sensitivity fluctuation is less than 5 dB, which meets the requirement of the practical engineering.

5. Conclusions

In this paper, we use the theory of optimized piezoelectric trilaminar designed an internal placed ICP piezoelectric accelerometer with its sensitivity being 800 mv/ms^{-2} (at 160 Hz). Based on the design theory of the co-vibration vector sensor, we made a high sensitivity (-185 dB, at 100 Hz), broad working band (10-2000 Hz) vector sensor. The outer diameter of it is 43 mm, and the length of it is 128 mm. This acoustic vector sensor has high sensitivity and small scale, and it has extensive application prospect.

Acknowledgements

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