

Study target detection performance of a single vector hydrophone

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Abstract. Vector hydrophone is a new measuring device of underwater acoustic signal. According to the actual project needs, for the detection of low-frequency weak targets and ensuring the effective recording of the sound field information, this paper designed a low noise vector hydrophone. Receiving system detection performance and self-noise was tested in anechoic tank. The test results show that the low-noise vector hydrophone with attitude correction system, which was designed in this paper, has pressure channel self-noise with 34.5 dB@1 kHz and 43 dB@1 kHz in attitude system and does not work. The self-noise level was lower than B&K 8105 standard hydrophone, and below zero sea condition ambient noise. A single vector hydrophone can complete DOA estimation for 0.024 V Gaussian white noise signal. Then we can get the SNR is -5.4 dB combined with anechoic tank ambient noise and signal levels. In other words, a single vector hydrophone can complete target detection when DT=-5.4 dB. According to this norm and according to the actual environment we can estimate the target detecting range.

Key words. Vector hydrophone, low-noise, attitude correction system, target detection.

1. Introduction

As a new measuring device of underwater acoustic signal, vector hydrophone is another hot research topic after scalar hydrophone. It can synchronously and concurrently measure the sound pressure and particle vibration velocity of one point in sound field space, thus providing more comprehensive sound field information and widening the signal processing means and space [1–6]. Compared to pressure hydrophone, single vector hydrophone possesses dipole directivity irrelevant to frequency and certain anti-isotropy noise ability, which enables it to realize the total-space non-fuzzy positioning of target and consequently have unique superiority in underwater sound detection field [7–13].

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According to practical engineering need, in order to detect low-frequency weak target and ensure effective recording of sound field information, it is required to seriously control the self-noise intensity of vector hydrophone, and the production of low-noise vector hydrophone is of great importance. Due to in practical application, vector hydrophone may be influenced by ocean current, internal wave, mobile platform and other factors to generate attitude changes like pitching, rolling, horizontal rotation. So, this paper designed a low-noise vector hydrophone with pressure channel, vector channel and attitude correction system, and target detection performance and self-noise were tested in anechoic tank.

2. Self-noise test for receiving system of vector hydrophone

Before practical engineering application of vector hydrophone, it is essential to conduct self-noise test of whole receiving system, which provides great guidance in designing and producing low-noise vector receiving system. The experimental vector receiving system is as shown in Fig. 1. The system is composed of two parts: wet end and dry end. The dry end is an independently designed and developed miniaturized acoustic signal collecting and processing system, which is composed of power panel, analog board and digiboard as well as four RS232 interfaces and one internet access, as shown in Fig. 2. The self-noise of entire vector receiving system includes vector hydrophone, transmission cable, acoustic signal collecting and processing system and external electromagnetic interference. Besides, there will be flow noise and other interference in the ocean. In order to ensure the effective recording of sound field information, the self-noise of vector receiving system must be controlled within certain range. In case there are no special instructions, the system noise referred to in the paper is mainly the self-noise from all channels of vector hydrophone.

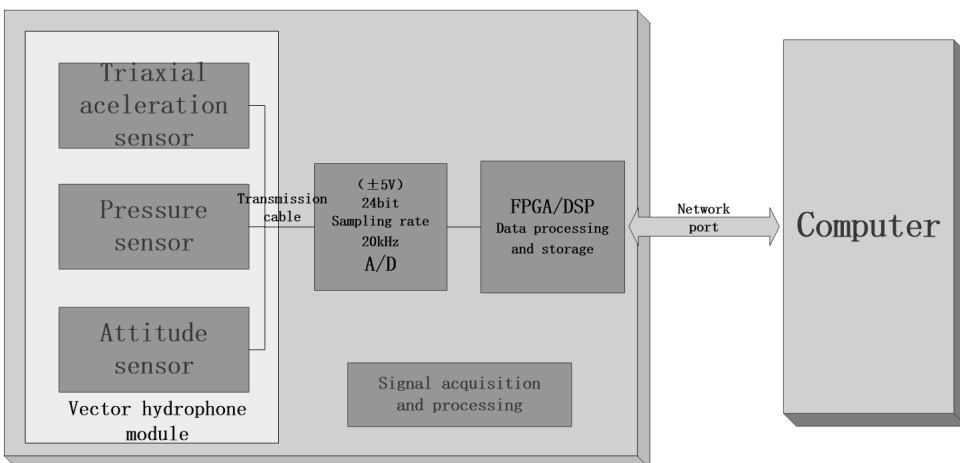


Fig. 1. The receiving system of vector hydrophone

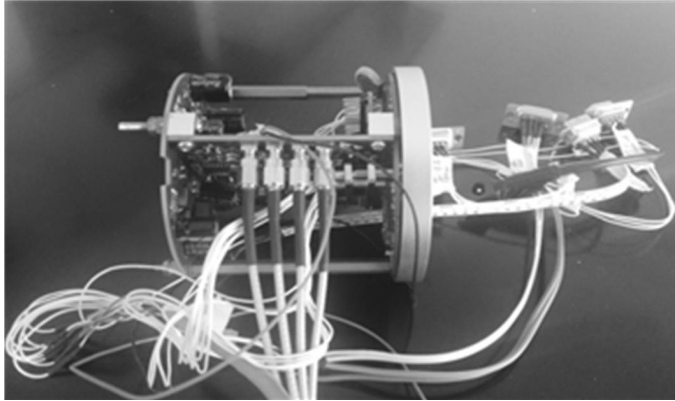


Fig. 2. Acoustic signal collecting and processing system

2.1. Sensitivity feature of vector hydrophone

The experimental vector hydrophone is an independently designed and developed accelerated three dimension co-vibrating vector hydrophone, as shown in Fig. 3.

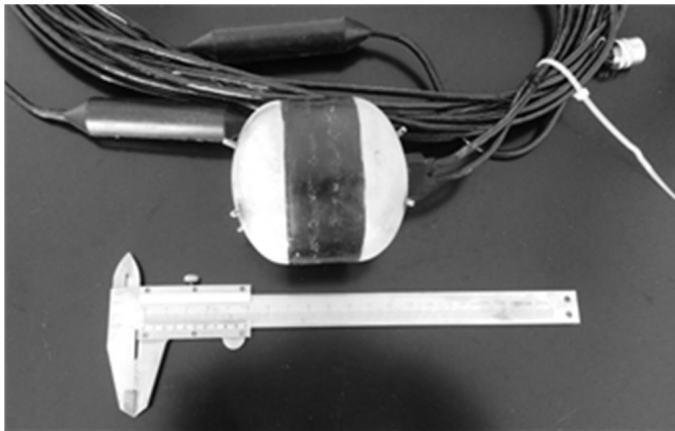


Fig. 3. The three dimension co-vibrating vector hydrophone

Sensitivity is an important indicator of vector hydrophone. Each sensitivity shall satisfy the relation below [1–4]

$$M_p = \frac{\omega}{\rho c} M_a = \frac{1}{\rho c} M_v = \frac{1}{\omega \rho c} M_\xi$$

In above equation, M_p is the equivalent pressure sensitivity of vector hydrophone, M_a denotes the acceleration sensitivity, M_v stands for the vibration sensitivity, and M_ξ is the displacement sensitivity. The independently developed vector hydrophone

received the standing wave tube test in Acoustic Level-I Metering Station approved by State Administration of Science, Technology and Industry for National Defense, which shows its pressure sensitivity level of pressure channel is -189 dB, and the equivalent pressure sensitivity of vector channel is proportional to frequency.

2.2. Self-noise test for vector receiving system

To verify the target detection performance of independently developed vector hydrophone and measure the self-noise level of whole vector receiving system, a 14-day test was carried out in anechoic tank. Figures 4 and 5 provide the self-noise test results of vector receiving system of vector hydrophone in two working conditions when attitude system work or does not work. For comparison, both figures display the self-noise test results of B&K8105 standard hydrophone and the changes of ambient ocean noise spectrum level with frequency under level-0 and level-6 sea condition by Knudsen curves. It can be found in Figs. 4 and 5 that:

(1) When the attitude system does not work, the self-noise spectrum level of pressure channel of vector hydrophone is less than that of B&K standard hydrophone within total frequency range except a few frequency points in low-frequency stage, and is less than ambient ocean noise under level-0 sea condition in high-frequency stage higher than 200 Hz.

(2) After the attitude system works, the self-noise spectrum level of pressure channel of vector hydrophone increases to some extent within total frequency range, and 1 kHz self-noise spectrum level goes up by 8.5 dB from 34.5 dB to 43 dB.

(3) The self-noise spectrum level of acceleration channel of vector hydrophone increases with decreasing frequency, which is because the equivalent pressure sensitivity of acceleration channel of vector hydrophone decreases with decreasing frequency. So, the lower the frequency is, the larger the self-noise spectrum level of acceleration channel will be. This makes the self-noise of acceleration channel to be maximum in low-frequency stage, approximating to the ambient ocean noise under level-6 sea condition.

(4) The working condition of attitude system has hardly any impact on self-noise of acceleration channel of vector hydrophone which is higher than self-noise of pressure channel and the ambient ocean noise under level-0 sea condition in the total frequency range.

From the above, what imposes greatest influence on the measurement performance of vector receiving system is attitude powered work and low-frequency self-noise of acceleration channel. Only when both the influence of attitude powered work on pressure channel self-noise and the low-frequency self-noise of acceleration channel are reduced to around the ambient ocean noise under level-0 sea condition, the effective acoustical signal of receiving system can be assured. To improve the detection performance of vector hydrophone and enable it to be suitable for signal detection of low-frequency weak target, each channel self-noise of vector hydrophone should satisfy

$$N_i(f) \leq NL(f) + NZ_i(f) - DI_i + M_i(f).$$

In the formula, $N_i(f)$ ($i = p, x, y, z$) is the self-noise spectrum level of each

channel of vector hydrophone, $NZ_i(f)$ is the noise spectrum level generated by attitude work, DI_i is the receiving directivity of vector hydrophone, and $M_i(f)$ is the equivalent pressure sensitivity of each channel of vector hydrophone. The above formula indicates three measures of reducing self-noise level of vector receiving system:

- (1) Enhance the manufacturing technique of vector hydrophone, and reduce the channel self-noise of vector hydrophone, particularly the low-frequency interference self-noise of vector channel.
- (2) Release electromagnetic shielding upon attitude measuring system to remove the influence from powered work of attitude system, especially the influence on pressure channel of vector hydrophone.
- (3) Increase the sensitivity of each channel of vector hydrophone.

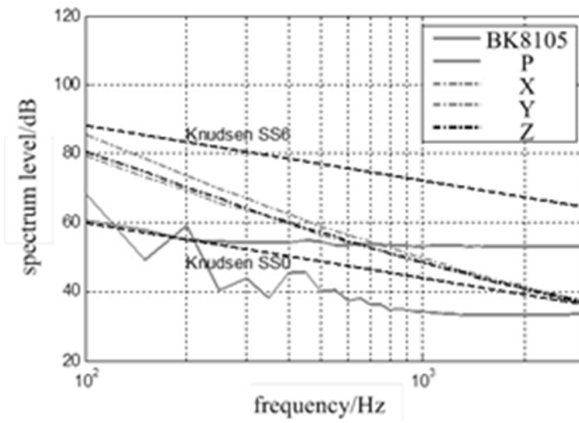


Fig. 4. Self-noise of vector system (attitude system does not work)

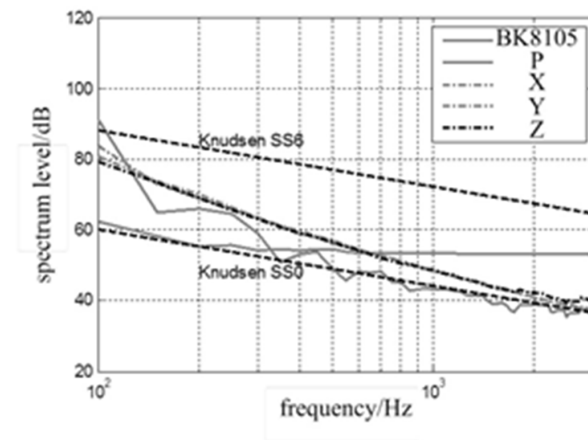


Fig. 5. Self-noise of vector system (attitude system works)

3. Detection performance test for vector hydrophone

This section aims at testing the target detection performance of independently developed vector hydrophone. There are a lot of single vector hydrophone based target orientation methods, but this paper mainly studies the re-acoustic energy flux based DOA estimation method for single vector hydrophone. This method has the ability to resist strong line spectrum interference and distinguish multi-target DOA of acoustic radiation in different frequency, and thus is the orientation estimation with maximum likelihood ratio.

3.1. Mathematical model of single vector hydrophone and the cross spectrum histogram orientation method

The vector hydrophone can synchronously and concurrently measure the sound pressure scalar at one point of sound field and the three orthogonal component of particle vibration velocity. In far field and plane wave condition, K signal model received by single vector hydrophone satisfies [11–13]

$$X(t) = A(\theta)S(t) + N(t)z.$$

Here, $S(t)$ is $K \times 1$ dimensional target signal vector, $N(t)$ is $K \times 1$ dimensional noise signal vector, and matrix $A(\theta)$ is $4 \times K$ dimensional array manifold vector, that can be written as:

$$A(\theta) = [a(\theta_1) \quad a(\theta_2) \quad \cdots \quad a(\theta_K)].$$

Here, $a(\theta_i) = [1 \quad \cos(\theta_i) \cos(\varphi_i) \quad \sin(\theta_i) \cos(\varphi_i) \quad \sin(\varphi_i)]^T$, is the array manifold of i th signal in single vector hydrophone, $(\cdot)^T$ represents the conjugate transpose, $\theta_i \in (0^\circ, 360^\circ)$ is the horizontal azimuth of i th arriving signal (the included angle with the X axis in positive direction), $\varphi_i \in (-90^\circ, 90^\circ)$ is the pitch angle of i th arriving signal (the included angle with XOY plane). It is observed that the array manifold vector is only relevant to azimuth and pitch angles of arrival signal, but irrelevant to time delay or frequency. Thus, when processing broadband signals, we can directly process received signals in time domain, rather than converting to frequency domain. What needs special attention is that before utilizing received signals to estimate DOA, it is a must to conduct de-DC or filtering processing. Otherwise, there will be great estimation bias in DOA. The expression of re-acoustic flux based histogram DOA estimation is briefed as

$$\theta(\omega) = \arctan \left(\frac{Re \langle P(\omega) V_y^*(\omega) \rangle}{Re \langle P(\omega) V_x^*(\omega) \rangle} \right),$$

$$k = [\theta(f) * 180/\pi],$$

$$\varphi(k) = \varphi(k) + 1.$$

Here, $\theta(\omega)$ is the target estimation azimuth of each frequency point, Re means the real part of signal, $P(\omega)$, $V_x(\omega)$ and $V_y(\omega)$ are the frequency spectra of the pressure

channel, X channel and Y channel signals for vector hydrophone, $\lfloor \cdot \rfloor$ denotes the rounding operation, and φ is the frequency of orientation estimation in all angles.

3.2. Detection performance analysis for vector hydrophone

The anti-interference gain of cross spectrum acoustic energy flux relates to time integration length. The longer the time integration is, the larger the anti-interference gain will be. But due to interference of ambient ocean noise, SNR gain of acoustic energy flux will not immortally increase with time integration, and there is a upper limit value. This paper adopted the cross spectrum histogram with different time integration lengths to analyze the detection performance of single vector hydrophone.

Then, we used the experimental data collected in anechoic tank to analyze the influence of time integration on target orientation. The test signals are Gaussian white noise output by signal source. Before conducting orientation analysis, first, it is required to calibrate working condition of sound source level so as to determine SNR of signal received by vector hydrophone. The peak Gaussian white noise output by signal source is set as 0.1 V, 1 V and 10 V respectively, and the power amplifier gain is set to be maximum. The test results are shown in Fig. 6. It can be seen when peak is 0.1 V, 1 V and 10 V respectively, the noise spectrum level is 57.5 dB@1 kHz, 76.5 dB@1 kHz and 96.3 dB@1 kHz, which basically satisfies the linear relation of $SL = 20 \log 10(P/P_0)$. From this, it can be calculated that the noise spectrum level of signal source that outputs peak 0.024 V Gaussian white noise is 43.9 dB@1 kHz, respectively.

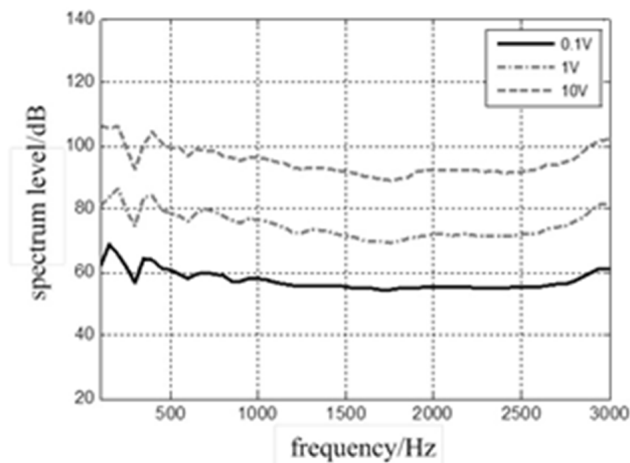


Fig. 6. Signal spectrum levels of Gaussian white noise

After completing the working condition calibration of sound source level, the power amplifier is shut down. At this moment, vector hydrophone's pressure channel is used to measure the background noise of tank, and the test result is 49.3 dB@1 kHz. Thus, by passive sonar equation, it can be calculated when the receiving signal source of pressure channel of vector hydrophone outputs peak 0.024 V Gaussian white noise,

its DT (signal to noise ratio) is -5.4 dB, respectively.

Figs. 7 top and bottom provide the target DOA estimation course chart for time integration length of 1 s and 17 s after implementing 800 Hz–5 kHz band-pass filtering pre-processing on peak 0.02 V Gaussian white noise signal. From above, it can be seen that by increasing time integration length, we can obtain ideal DOA estimation results and improve the target detection performance of vector hydrophone in high/low SNR condition.

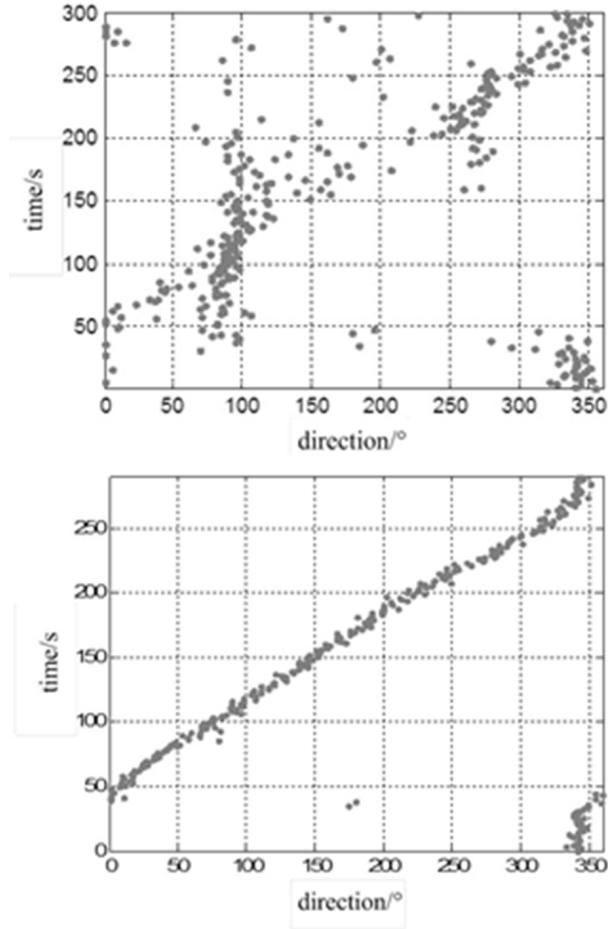


Fig. 7. The orientation course chart for peak 0.024V Gaussian white noise: top–time integration is 1 s, bottom–time integration is 17 s

From the above analysis, it is known that the independently developed vector hydrophone can correctly estimate the target DOA through time integration when SNR (i.e. DT) is -5.4 dB, which can be taken as an important parameter indicator of vector hydrophone. According to this indicator and combined with practical ocean

condition, the target detection range can be predicted.

4. Conclusion

According to practical engineering needs, this paper designs and produces a low-noise vector hydrophone with attitude measuring system and a miniaturized vector receiving system. The anechoic tank measuring results indicate that:

(1) When the attitude system does not work, the pressure channel self-noise of vector hydrophone is lower than B&K8105 standard hydrophone self-noise. And in high-frequency stage higher than 200 Hz, the self-noise spectrum level is lower than ambient ocean noise in level-0 sea condition;

(2) After the attitude system works, the pressure channel self-noise of vector hydrophone goes up in the whole frequency range, without any effect on vector channel.

(3) The vector hydrophone can complete target orientation when $DT = 5.4$ dB. According to this indicator and combined with practical ambient ocean condition, the target detection range can be predicted.

Above test results the paper provides important guiding significance to further reduce vector hydrophone self-noise level and improve target detection performance.

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