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A Bionic Fish Cilia Median-Low Frequency Three-Dimensional Piezoresistive MEMS Vector Hydrophone

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Abstract: A bionic fish cilia median-low frequency three-dimensional MEMS vector hydrophone is reported in this paper. The piezoresistive reasonable position was obtained through finite element analysis by ANSYS and the structure was formed by MEMS processes including lithography, ion implantation, PECVD and etching, *etc.* The standing wave barrel results show that the lowest sensitivity of the hydrophone is −200 dB and reach up to −160 dB (in which the voltage amplification factor is 300). It has a good frequency response characteristics in 25 Hz ∼ 1500 Hz band. Directivity tests displayed that the hydrophone has a good "8"-shaped directivity, in which the resolution is not less than 30 dB, and asymmetry of the maximum axial sensitivity value is less than 1.2 dB.
Keywords: MEMS vector hydrophone; Bionic; ANSYS; Median-low frequency

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Introduction

With the development of underwater acoustical warfare, high frequency noise radiated by underwater motion platform has greatly reduced. Especially after anechoic tile using on majority of submarines, the working frequency of senor has dropped to below 3 kHz, which makes the underwater acoustic detection to the median-low frequency [1,2]. To obtain the spatial gain with small scale senor array at low frequency and precisely azimuth information as the underwater target, vector hydrophone is a best choice [3,4]. Mostly, traditional co-vibrating vector hydrophones adopt move coil or piezoelectric principle [5].

In recent years, the detection for underwater acoustic signals with a variety of new sensing mechanism was reported. For example, a PVDF film hydrophone made by Britain and France has been used in their submarines. Bionics is the application of biological methods and systems found in nature to the study and design of engineering systems and modern technology. The two-dimensional bionic vector hydrophone developed by North University in China is a new type of vector hydrophone, which has the advantages of small size, vector character, low-cost, easy installation, *etc* [6]. However, as a two-dimensional vector hydrophone, it is not useful in spatial localization. Therefore, there is an urgent need to develop a three-dimensional MEMS vector hydrophone.

In this paper, we developed a three-dimensional MEMS vector hydrophone based on fish cilia and piezoresistive principle. The detailed design, fabrication, and performance test are discussed in the following sections.

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Sensor design and analysis

The lateral line, as a sensory organ, is peculiar to fish and amphibians. Figure 1 shows the fish lateral line which consists of cilium shape mechanoreceptors or neuromasts. It is covered with a jelly-like cupola located on the skin or in the canals along the body. When the pressure of water is changed by acoustic waves, the fluid motion gets into pore through lateral line and delivers to mucus. This will cause the flowing of mucus which makes the displacement of hair cell. Sensory cells can be stimulated and the stimulation is transmitted to medulla oblongata by nerve fiber and the fish will react according to the signal.

According to the above fish lateral line structure, a three-dimensional MEMS vector hydrophone was designed as shown in Fig. 2. The sensor hair was imitated by rigid cylinder (X and Y direction) and long cantilever beam (Z direction). The sensory cells and efferent nerve were imitated by the piezoresistors and metal lead, respectively. Moreover, the piezoresistors of X and Y direction were linked by full wheat stone bridge. Whereas, the piezoresistors on each of two cantilever beam of Z direction were linked by half wheatstone bridge to form two half bridge, and the signal of two half bridges was added to make up for the deficiencies of low sensitivity of the half bridge.

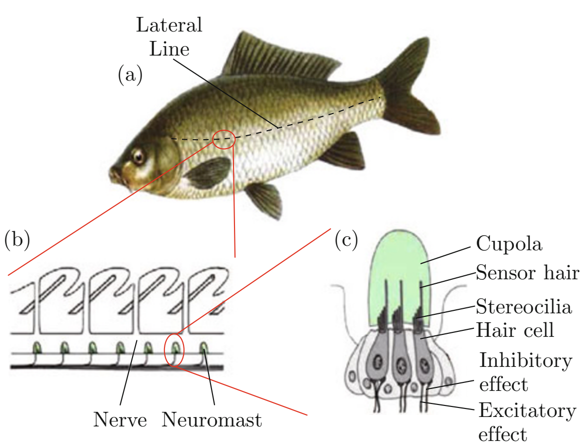

Fig. 1 Schematic drawing of fish lateral line.

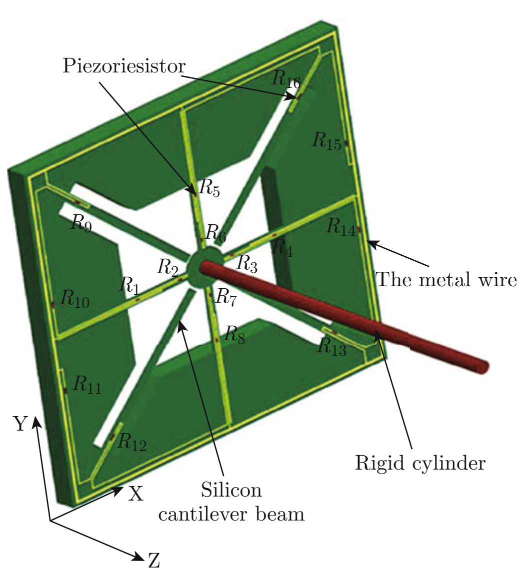

Fig. 2 Schematic of the bionic MEMS hydrophone.

According to the acoustics theory, when $k\alpha \ll 1$ (k is wavenumber and α is the hydrophone radial size), the scattering of incident acoustic wave caused by vector hydrophone can be ignored. In the condition of far field, the vector hydrophone is equivalent to water particles, as shown in Fig. 3.

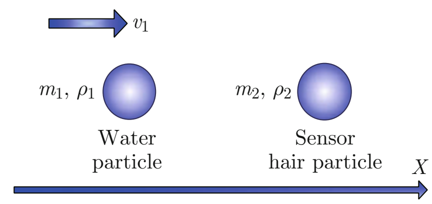

Fig. 3 Water particle with sensor hair particle.

In the acoustic perturbation, water particles begin to move and the momentum of water particles with nerve fiber is conservation in the instant of collision, that is:

$$m_1\bar{v}_1 = m_1\bar{v}_1' + m_2\bar{v}_2$$

where, m_1 and m_2 is the mass of water particles and nerve fiber respectively; $\bar{v}_1$ is the vibration velocity of water particles before the collision; $\bar{v}_1'$ and $\bar{v}_2$ is respectively the vibration velocity of water particles and nerve fiber after the collision.

As shown in Fig. 4, the orthogonal decomposition of

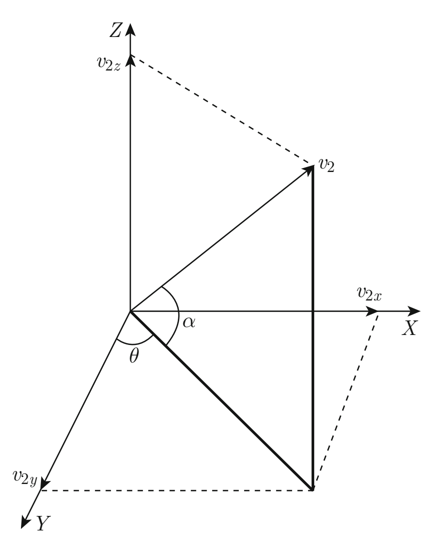

Fig. 4 Orthogonal decomposition of $\bar{v}_2$.

$\bar{v}_2$ is $\bar{v}_{2x}$, $\bar{v}_{2y}$, $\bar{v}_{2z}$,

$$v_{2x} = v_2 \cos\theta \cos\alpha \tag{1}$$

$$v_{2y} = v_2 \sin\theta \cos\alpha \tag{2}$$

$$v_{2z} = v_2 \sin\alpha \tag{3}$$

so,

$$\theta = ac\tan\left(\frac{v_{2y}}{v_{2x}}\right) \tag{4}$$

$$\alpha = ac\tan\left(\frac{v_{2z}}{\sqrt{v_{2x}^2 + v_{2y}^2}}\right) \tag{5}$$

From all above we can come to the conclusion that the acoustic propagation characteristics can be detected by testing movement of the nerve fiber.

Simulation and fabrication

It is well known, the piezoresistive effect represents the change in electrical resistivity of a semiconductor when mechanical stress is applied. The piezoresistance expression of silicon cantilever is $\Delta R/R = \sigma_l \pi_l + \sigma_t \pi_t$. For the piezoresistors with P-type $\langle 110 \rangle$ crystal orientation, $\pi_l = 71.8 \times 10^{-11}$ Pa^{-1}, and $\pi_t = -66.3 \times 10^{-11}$ Pa^{-1}, respectively. Generally, when external force acts on the cantilever, its shear stress σ_t can be neglected for far less than normal stress σ_l. So the mechanical sensitivity of the vector hydrophone would be expressed as: $S = 71.8 \times 10^{-11} \sigma_l V_{in}/P$ (where V_{in} is the input voltage, and P is the sound pressure) [7]. In order to obtain a maximum sensitivity, the piezoresistor cannot be placed in the maximum stress area and the nonlinear area.

The stress of the MEMS hydrophone was analyzed using ANSYS where 1 Pa loads were added along the Y direction of the rigid cylinder and Z direction to the cantilever beam. The stress-contour of the structures are shown in Fig. 5(a) and Fig. 6(a), whereas, the stress curves of one beam obtained by path definition in ANSYS are shown in Fig. 5(b) and Fig. 6(b).

According to the piezoresistor distribution principle, the simulation piezoresistor distribution graph was marked in Fig. 5(b) and Fig. 6(b), where there were about 100 μm from the end of cross-beam and 200 μm from the roots of silicon cantilever. Moreover, the transverse stress of cross-beam X direction was approximated to zero in symmetrical distribution as shown in Fig. 5 and Fig. 6.

The MEMS hydrophone microstructure was fabricated by standard MEMS process using 4-inch SOI wafers with the electrical resistivity of 2∼4 Ω·cm, the active layer thickness of 20 μm, the buried oxide layer thickness of 2 μm and handle wafer thickness of 400 μm. The MEMS fabrication technological processes are

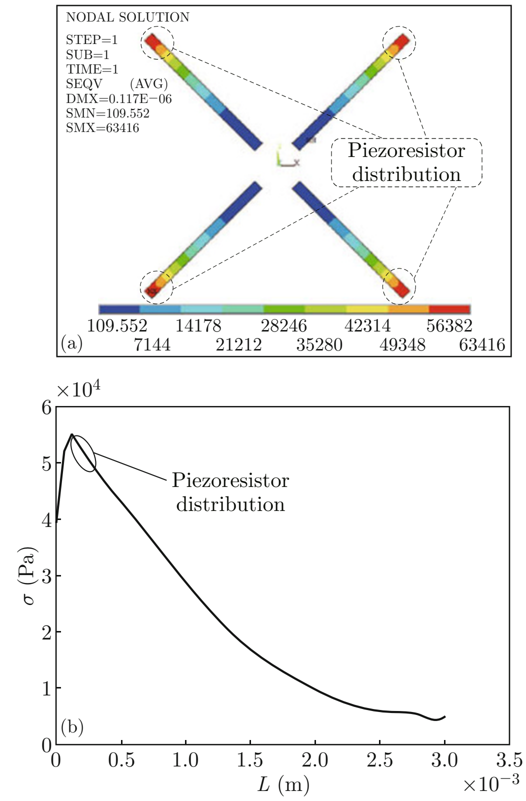

Fig. 5 (a) The stress-contour of cantilever beam; (b) Curve of cantilever stress distribution.

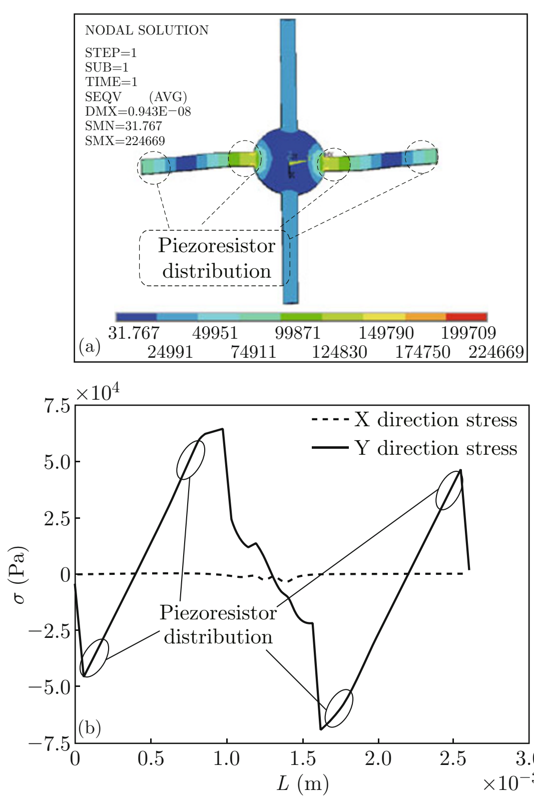

Fig. 6 (a) The stress-contour of cross-beam; (b) Curve of cross-beam stress distribution.

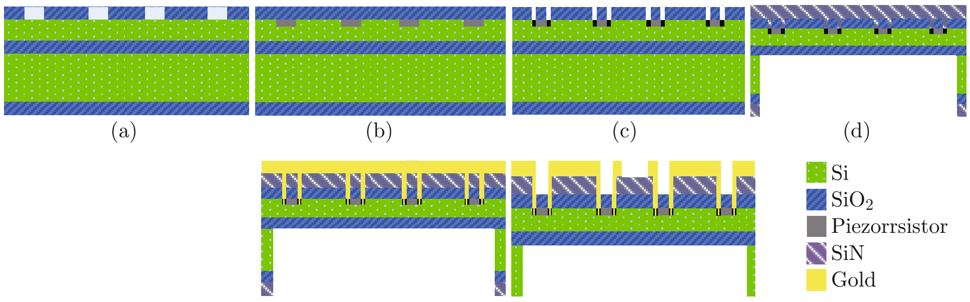

Fig. 7 The process of manufacturing technology. (a) Oxidation and ICP etching; (b) Implant boron to form piezoresistors and re-oxidation; (c) ICP etching and implantation dense boron; (d) PECVD epitaxy and ICP etching; (e) ICP etching and sputtering gold; (f) Gold etching and release the structure.

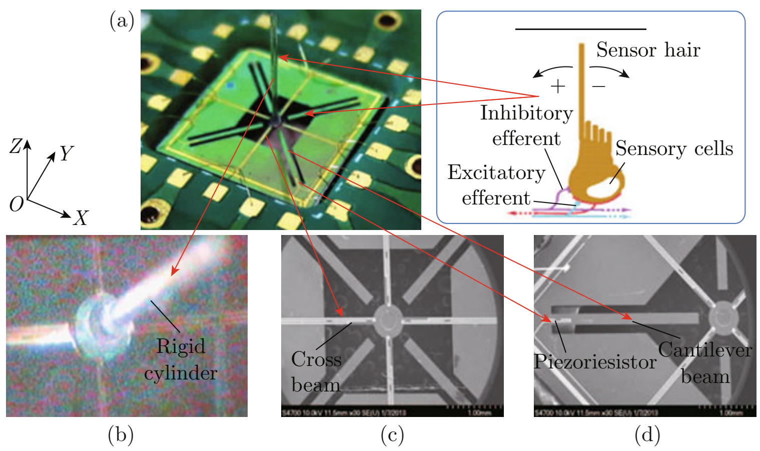

Fig. 8 Images of the hydrophone microstructure.

shown in Fig. 7, including oxidation, ICP etching, ion implantation, films growth and vapor plating processes.

Bionic package and test

Figure 8 shows the images of the hydrophone microstructure. To perform an underwater test of the MEMS vector hydrophone, the microstructure must be packaged to avoid damage. The package structure not only has a protective effect, but ensures the external sound signal to the maximum transfer to biomimetic cilia. According to the neuromast model shown in Fig. 1(c), bionic package structure was made. The bionic package structure is composed of two parts: transferal acoustic cap manufactured by the polyurethane [8,9] with better acoustic properties and silicone oil which is used to fill into the acoustic cap. The detailed package structure is shown in Fig. 9.

To verify the rationality and feasibility of the hydrophone structure, the receiver sensitivity and directivity pattern of the MEMS bionic vector hydrophone was investigated in the standing wave tube calibration device. Figure 10 shows the principle of calibration device. The receiver sensitivity test adopted the antitheses calibration method compared the voltage output of tested MEMS hydrophone with the reference hydrophone. The test frequency is in the range of 25 Hz∼3.5 kHz. The vector hydrophone was fixed parallel to the acoustic wave propagation direction of the standing wave tube calibration device along direction X, Y and Z, respectively. Put the experiment data, which were recorded at the frequency of 1/3 octave band, into the formula [10],

$$M_x = M_0 e_x \sin kd / e_0 \cos kd \tag{6}$$

where M_0 is the receiving sensitivity of reference hydrophone, e_x and e_o is respectively the open-circuit

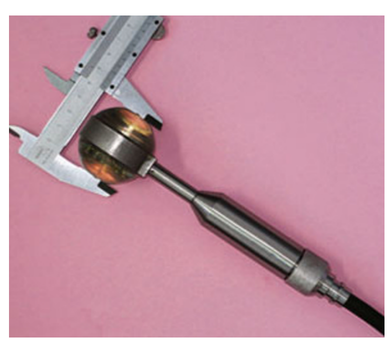

Fig. 9 Image of MEMS vector hydrophone.

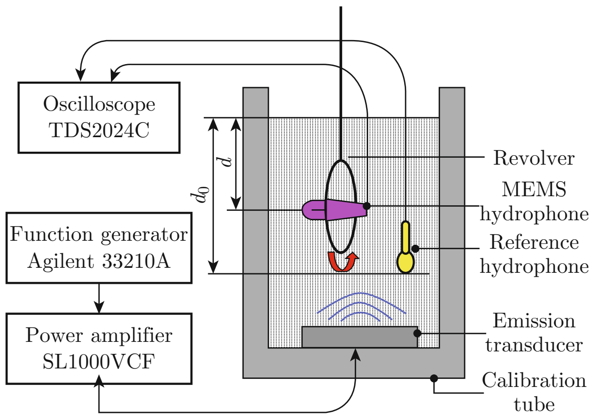

Fig. 10 The standing wave tube calibration device.

voltage of vector hydrophone and reference hydrophone, k is wavenumber, and d is the distance from water surface to the hydrophone. One can obtain the frequency response curve in the range of 25 Hz∼1.5 kHz (see Fig. 11). This curve is approximated as a linear law, and sensitivity range of key direction is from −160 dB to −200 dB when the the voltage amplification factor is 300.

A mechanical rotary rod was used to rotate the vector hydrophone along horizontal axis in order to change the receiving direction of sound source. We recorded the vector hydrophone sensitive in each direction. When putting the test data into the following formula [11],

$$L = 20\log(e_\theta/e_{\max}) \tag{7}$$

where L is the normalized data, e_θ and $e_{\max}$ is respectively the voltage of arbitrary direction and the maximum direction of the vector hydrophone, the directivity pattern can be obtained. Figure 12 shows the directivity pattern at the frequency 500 Hz. It can be seen there is a smooth "8" shape graph for the vector hydrophone. The directional resolution, which is the ratio of hydrophone axial maximum sensitivity with transverse minimum sensitivity at one certain frequency, is no less than 30 dB.

Conclusions

A median-low frequency three-dimensional MEMS vector hydrophone is presented in this paper. The hydrophone has the advantages of small size, simple

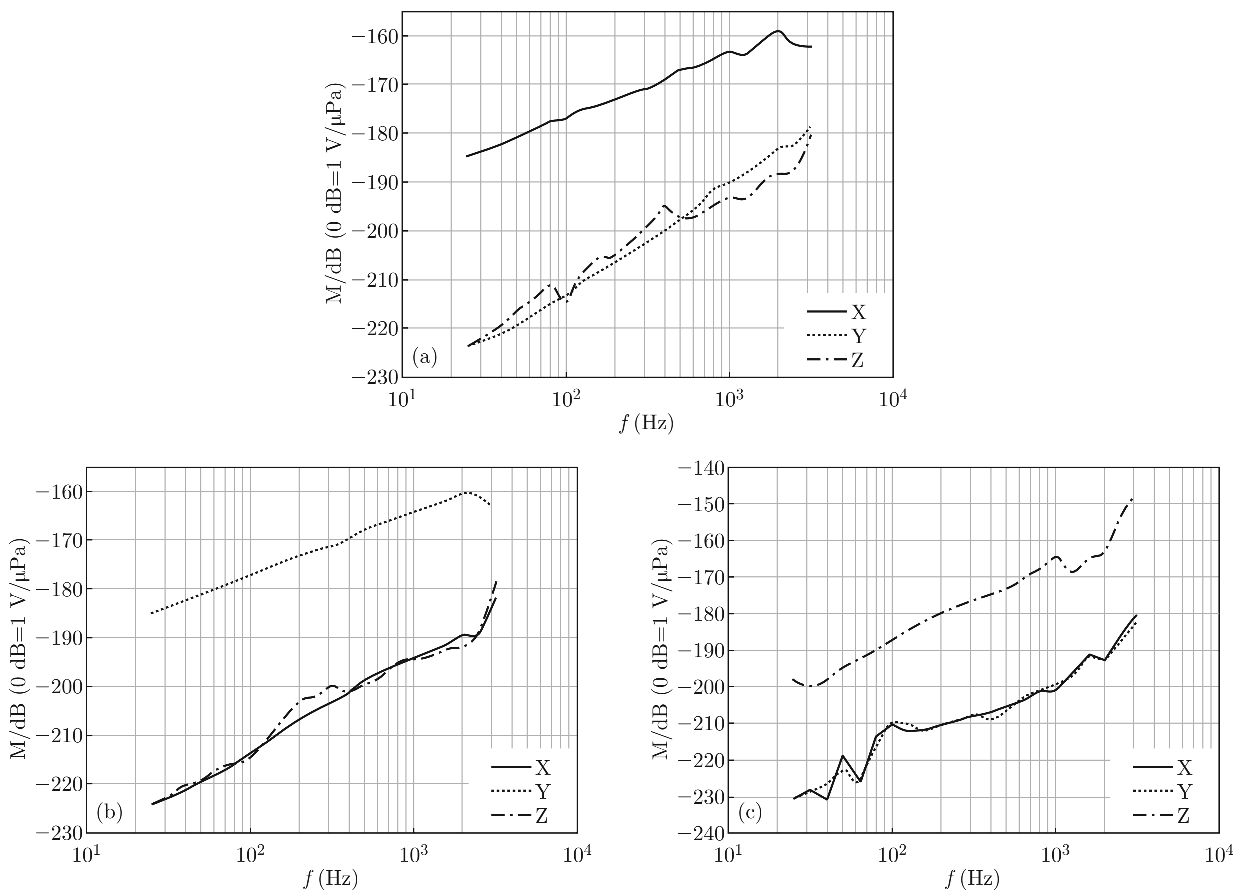

Fig. 11 (a) Frequency response curve of X direction (attenuation of 20 dB); (b) Frequency response curve of Y direction (attenuation of 20 dB); (c) Frequency response curve of Z direction (attenuation of 20 dB).

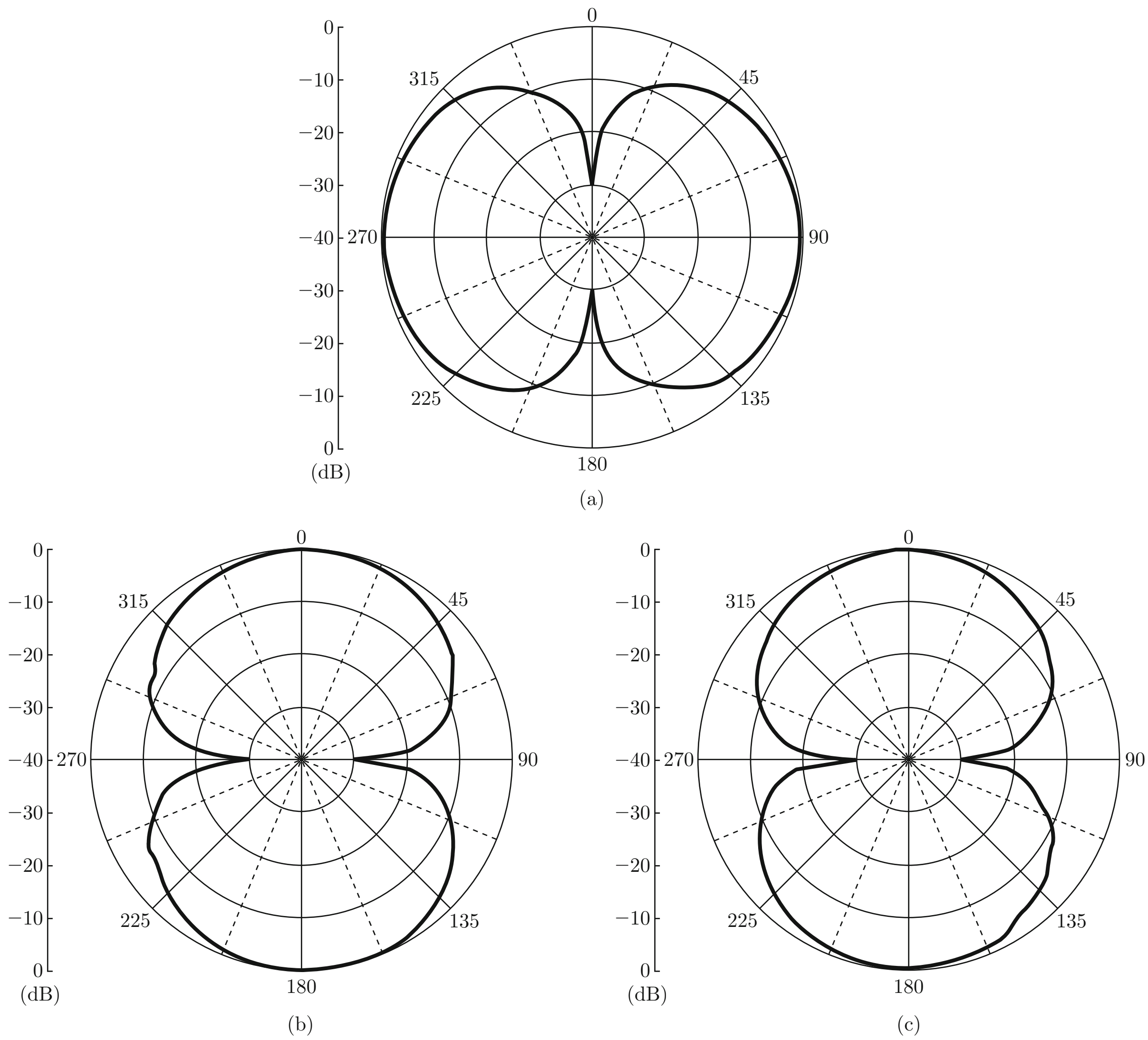

Fig. 12 (a) Directivity pattern of X direction; (b) Directivity pattern of Y direction; (c) Directivity pattern of Z direction.

manufacturing and high sensitivity. According to the test results, the hydrophone has a good frequency response in the range of 25 Hz∼1500 Hz, and its sensitivity can reach up to −180 dB. Directivity tests displayed that the hydrophone has a good "8"-shaped directivity, whose resolution was not less than 30 B. The improvement of the hydrophone sensitivity and expanding its available band are under ongoing.

Acknowledgement

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