A Design Method of Image Sonar

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Abstract. By analyzing the underwater high-speed target tracking and positioning, image sonar was determined as the solution. An image sonar system is constructed. According to the functions of each part of the image sonar, the transducer array, receiver, transmitter and image generation signal processing software are designed. According to the difficulties in the construction of the image sonar system, emphatically introduces the design of the transducer array and receiver. According to the principle of image sonar, designed by 128 piezoelectric ceramic elements joining together, form a circular receiving transducer array. The characteristics of image sonar receiver are multi-channel synchronous receiving and acquisition, high frequency and large amount of data. According to these characteristics, the analog front-end chip and FPGA are adopted as the core for the design. It realizes signal synchronous acquisition, orthogonal filtering, storage and Gigabit Ethernet communication functions. A computer platform is used for beamforming signal processing. It implements data read, phase-shift beamforming and matched filtering, and other functions. By integrating the above hardware and software functions, an underwater high-speed target tracking and positioning systems formed.

Keywords: Tracking and positioning; Image sonar; Transducer array; Synchronous receiving and acquisition; Beamforming.

1. Introduction
With the acceleration of ocean development in various countries, the development of various underwater high-speed vehicles is also accelerating. In order to make the development of high speed vehicle proceed smoothly, the corresponding supporting test equipment is also being developed. The need of tracking and positioning for measuring the trajectory of high speed vehicle arises. With the development of sonar technology, image sonar has become an important method of underwater high-speed target detection and positioning. Image sonar is a device that forms an image through multi-beam imaging technology to intuitively reflect the underwater scene. It has been widely used in ocean resource observation, target detection and ocean mapping [1].

Image sonar has passive mode and active mode according to its working mode. The passive mode is to use the noise radiation characteristics of the detected target to detect and locate. Its advantage is that the system is simple, no transmitting system is needed, the number of sensors is small, and the algorithm is relatively simple. But its disadvantage is that the observation error is large. The active mode is to transmit high-frequency acoustic pulse, detect target echo and give target trajectory, and its detection accuracy is higher than the passive mode [2]. In this paper, the image sonar system is designed in an active mode. And mainly from the core parts of the system, the design of transducer array and receiver is described and analyzed.
2. Construction of Image Sonar System

The hardware structure of the image sonar is mainly composed of a transducer array, a receiver, a transmitter, and a computer, as shown in Fig. 1. The transducer array is designed as a whole, including transmitting transducer array and receiving transducer array. The function of the transmitter is to generate an FM signal and drive the transmitting transducer through a power amplifier to transmit the generated acoustic signal. There is a communication interface between transmitter and the receiver, so that the receiver can obtain the time when the transmitter transmits the signal. The function of the receiver is to conduct analog preprocessing, sampling, orthogonal filtering and sampling storage for the weak reflected signals of underwater targets, and transmit the data to the computer through Ethernet. The computer obtains the data stored in the receiver via Ethernet, performs phase-shifted beamforming, matched filtering, two-dimensional image noise reduction and enhancement to form a two-dimensional image. Through the above hardware and software integration, an image sonar system is constructed.

![Block diagram of image sonar.](image1)

3. Image Sonar Design and Implementation

3.1. Transducer Array Design

The transducer array is designed as a whole, as shown in Fig. 2. Based on the use scenario and requirements of the image sonar, it is necessary to track and locate the target within 360 ° in the circumferential direction and within a distance of 100 meters, so the transducer array is designed in a ring shape. Combined with the propagation attenuation characteristics of sound waves in water, the higher the frequency, the faster the sound intensity decays. Considering the size of the transducer, the center operating frequency is 165 kHz. According to this principle, the parameters of the transducer are calculated.

![Schematic of transducer array.](image2)

In order to achieve the minimum physical open angle of the beam, the array is designed for the largest diameter Φ 180 mm. Considering that the thickness of the sound-transmitting rubber is generally not less than 4mm, the diameter of the outer of the receiving array element is designed to be Φ172mm. The array uses a piezoelectric composite strip mosaic process, and the size of each piezoelectric composite strip is designed to be 18 × 3 × 8 (thickness vibration direction) mm. The maximum operating frequency of the array is 170kHz. According to the half-wavelength array principle, the spacing between piezoelectric composite strips shall not be greater than 4.41mm. Synthesizing the outer diameter of the array, the size of the piezoelectric composite strips and the element spacing, the 128 piezoelectric composite elements are mosaiced, and the element spacing is 4.22mm, which meets the half-wavelength condition. The effective height of the array is the length of the piezoelectric composite strip, which is 18mm; Considering that printed circuit boards are used to weld piezoelectric composite strips on both sides of the array. The thickness of printed circuit board on each side is 5mm. Therefore, the size of this type of array is Φ180 × Φ130 × 35mm, as shown in Fig. 3.
Based on the beamwidth formulas of the point source equidistant circular array and continuous linear array, it is calculated that the beamwidth of this size array can be $2.1^\circ$ in the horizontal direction and $24.7^\circ$ in the vertical direction through electronic beamforming at 170kHz.

### 3.2. Receiver Design

The receiver is the core component of the image sonar hardware system. Its performance largely determines the performance of the image sonar. According to the phase shifting beamforming algorithm of the image sonar, the design of the receiver must comply with the principle of signal consistency between channels, otherwise the accuracy of target positioning will be directly affected. According to the propagation attenuation characteristics of sound waves in water, the receiver needs to design a time gain control module (TGC) to compensate the echo intensity of the target according to the time curve. According to the above analysis, if the traditional method is adopted, one analog/digital conversion chip is used for sampling in each channel, not only the circuit scale is huge, but also the synchronous acquisition design between each channel is difficult, which seriously affects the performance of the receiver. Therefore, this paper chooses TI company's analog front-end chip AFE5818 to design the front-end sampling circuit, and then chooses the flexible and efficient FPGA(Field Programmable Gate Array) chip to design the digital circuit. The analog front-end chip AFE5818 is powerful and especially suitable for ultrasound equipment and sonar imaging equipment. The main function of AFE5818 is a 16-channel complete analog front-end, including low-noise op amp (LNA), voltage-controlled attenuator (VCAT), programmable gain amplifier (PGA), low-pass filter (LPF), analog-to-digital conversion (ADC), and CW mixer.

- The low-noise operational amplifier LNA has programmable gains: 24dB, 18dB, and 12dB; corresponding linear input ranges: 0.25VPP, 0.5VPP, and 1VPP.
- Voltage-controlled attenuator (VCAT) attenuation range: 0 ~ 40dB.
- Programmable gain amplifier (PGA): 24dB and 30dB.
- Analog-to-digital converter (ADC): 14-bit ADC: 65MSPS sampling rate; 12-bit ADC: 80MSPS sampling rate.
- Low-voltage differential signaling (LVDS) interface with a maximum speed of 1Gbps.

In this paper, only 8 pieces of AFE5818 can meet the requirement of 128 sampling channels, and the circuit scale is greatly reduced. The attenuation range of its integrated voltage-controlled attenuator (VCAT) is $0 \sim 40$ dB, calculated according to sonar equation 1:

$$SL \approx 2TL + TS = DT$$  \hspace{1cm} (1)

In the formula: SL is the emission sound source level, take 200dB; TS is the target strength, taking -20db; DT is the detection valve. TL is the transmission loss, which includes the expansion loss and the absorption loss, as shown in Equation 2:
In the formula: \( r \) is the distance, \( \alpha \) is the Absorption coefficient, take 45dB/km; Assuming the sensitivity M of the receiving hydrophone is -200dB, when the target is 100 meters, the sound pressure level PL of the signal received by the hydrophone is:

\[
PL = 200 - 2 \times 20\log_{10} 100 - 0.2 \times 45 - 20 = 91\text{dB}
\]

Then the effective value \( U_0 \) of the hydrophone output voltage can be calculated as:

\[
U_0 = 10^{\frac{M + PL}{20}} = 3.5\mu V
\]

When the receiver gain is 78dB, the effective value of the output voltage is 29mV. It can also be calculated that when the target is at 2 meters, the effective value of the hydrophone output is 25mV. When the gain is 40dB, the front-end output voltage is 2.5V. Therefore, the fixed amplification gain of 40dB and adjustable gain of 0 ~ 38dB can meet the project requirements. From the calculation results, it can be seen that when a 14-bit AD chip is selected and the sampling amplitude is ± 5V, the voltage resolution is 0.6mV, which can cover the index requirements of the calculated amplitude from 41mV to 3.5V. Therefore, the selected AFE5818 meets the design requirements.

The command of AFE5818 is realized through SPI bus, and only three wires are needed to realize the communication function. The output of A/D conversion result of AFE5818 is in the form of low-voltage differential (LVDS), and the sampled data of its 16 channels has 16 parallel data lines. Therefore, FPGA chip with flexible design and parallel operation is the first choice. According to the estimation of required resources of the project, the FPGA model selected is XILINX XC7K325TFFG676 chip. The chip has 326,080 logical cells and 400 user IO ports, which can meet the design resource requirements of this project.

The receiver is functionally divided into front-end circuit and digital circuit. The front-end circuit is based on the analog front-end chip AFE5818. Digital circuit is designed with FPGA as the core. The receiver design block diagram is shown as in Fig.4. The FPGA needs to control the sampling of the analog front-end chip, perform orthogonal demodulation, low-pass filtering, pumping point output, storage and Ethernet communication on the collected 128-channel signals. These functions are designed and implemented through the hardware programming language Verilog.

**Figure 4.** The receiver block diagram.

### 3.3. Transmitter Design

The function of the transmitter is to transmitting a specific acoustic signal of a certain source level through the transmitting transducer. The signal transmitted in this project is a hyperbolic FM signal with a pulse width of 2ms. The signal frequency is 155kHz ~ 165kHz, and the source level reaches 200dB. Since the emitted signal is a fixed signal, the generated digital signal can be stored in ROM through FPGA design, as shown in Fig.5. First, a hyperbolic frequency modulation signal with sampling rate of 1MHz, pulse width of 2ms and frequency of 155kHz ~ 165kHz was generated by...
MATLAB software. The generated signal data is a signed binary complement data format with a capacity of 2k × 16bit. Secondly, it can be calculated that a target at a distance of 100 meters the propagation time of the detection echo is about 143 ms, which is taken as 200 ms here. Then the image sonar refresh frequency is 5Hz. The acoustic pulses transmitted by the transmitter are also transmitted at a period of 200 ms. The time of each transmission signal is transmitted to the receiver, which controls the gain of the received signal.

![Transmitter Block Diagram](image)

**Figure 5.** Transmitter Block Diagram.

### 3.4. Image Generation Signal Processing Software Design

Beamforming is another core technology of image sonar. It performs a certain delay processing on the signals received by each array element to compensate for the time delay difference caused by the spatial position of the incident wave in a certain direction. The delayed data is added to obtain a beam output pointing in that direction. In digital systems, this "delay-sum" beamforming method is implemented by shifting and superimposing sequences. The accuracy of the delay is directly proportional to the data sampling rate. This project uses a phase-shifted beamforming method, which uses phase compensation to approximate the delay adjustment, and superimposes the phase-compensated reception sequence to obtain the beam output.

### 4. Conclusion

Through the construction of image sonar system, a method of underwater high-speed target tracking and positioning is designed. Through the function design of each part of image sonar, the design method of transducer array and receiver is introduced. Through engineering verification, this method can well track and locate underwater high-speed targets. This method provides a good reference for image sonar design. It enriches the method of high speed target tracking. Next, the signal processing method will be studied to provide a complete set of hardware and software design ideas.

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