Study of Ultrasonic Phased Array in Underwater Welding

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Abstract The popular sensors used in water have a lot of difficulties when compared with those used in land welding automation. It is meaningful to find a new kind of sensor which is suitable to work in underwater welding. Ultrasonic phased array (PA) can work in water conveniently and send out required sound beam. Compared with single-ultrasonic sensor, PA works faster and effectively. In this chapter, interference principle of acoustic beam is analyzed first. Then, the relationship of focusing precision, PA shape, gap distance between adjacent units, sensor element number, and time resolution is revealed with simulation. Proper physical parameters of PA are determined. At last, high time resolution circuit based on complex programmable logic device (CPLD) is given out. It works together with sound-emitting and -receiving circuits to realize fast scan on welding workpiece, so that the seam line can be deduced with underwater distance detection.

Keywords Underwater welding · Ultrasonic phased array · Sound interference
Circuit design

1 Introduction

Ocean plays a significant role in keeping sustainable development of our world, so wet welding technology is becoming more and more important with the continuous increase of marine engineering. The wet welding studies are mainly focused on welding method, welding stability, and welding material, Gao et al. [1] studied underwater friction stud welding. Mori et al. [2] studied underwater explosive welding of tungsten. Hu et al. [3] studied the arc stability of wet manual welding.

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Mazzaferro and Machado [4] studied arc stability in underwater shielded metal arc welding at shallow depths. Guo et al. [5, 6] studied metal transfer at shallow water. As for wet welding automation, the biggest problem lies in that almost all the sensors are hard to work in water. It is well known that the popular welding sensors are charge-coupled device (CCD) cameras and rotating arc sensors [7, 8], but both are unsuitable for wet welding. For the cameras, they must be sealed in a transparent box to prevent water, and auxiliary illuminator is always needed for intensifying illumination. Besides these, images are influenced inevitably by arc lights, vapor bubbles, and substance suspending in water. Regarding the rotating arc sensors, they cannot work directly in water either. How to confirm the electric motor to run reliably in water is a big problem to be solved first. Another problem is that the length of welding arc is affected by water pressure markedly. The arc length shortens and the arc width attenuates while the water pressure increases. If the pressure becomes big enough, the welding arc may be extinguished.

Because welding automation is based on high-performance sensor, it is imperative to look for a new one for wet welding. Previous research indicates that ultrasonic sensor can work directly in water, and sound beam is insensitive to arc light and steam vapor [9]. In addition, precise distance detection between workpiece and sensor has been fulfilled in water with ultrasonic sensor by means of cross-correlation [10–12]. Based on these, ultrasonic phased array (PA) is introduced in our work. PA consists of tens or even hundreds small units. These tiny parts may also be called transducers or units, and often be arranged in line, in circle, or other specific shapes. All the units can be driven separately, so the sound beam may be focused on the expected positions quickly and conveniently without any mechanical movements. The form of workpiece can be obtained by way of distance detection. It is clear that PA is much more flexible and effective than single-ultrasonic sensor in wet welding.

The rest of this chapter is arranged as follows. Section 2 introduces Huygens' principle which points out the requirements of how to get steady sound wave interference, and then, by help of software simulation, the proper physical parameters of PA sensor are determined, including the shape, the number of units, and the gap distance between adjacent elements. Section 3 introduces electric circuits which are designed for producing high-resolution time sequence, generating excitation signal, sending sound wave, and receiving sound wave.

2 Physical Parameter Determination of PA

PA is constructed by a set of small transducers with different shape and size. Acoustic waves are emitted from these small units and interact with each other in water. To confirm multi-waves focused on a specific point (generally speaking, this point is on the surface of workpiece), the beams must meet some conditions. According to Huygens' principle, the waves should have the same frequency and stable phase difference. The synthetic wave has the biggest amplitude when the

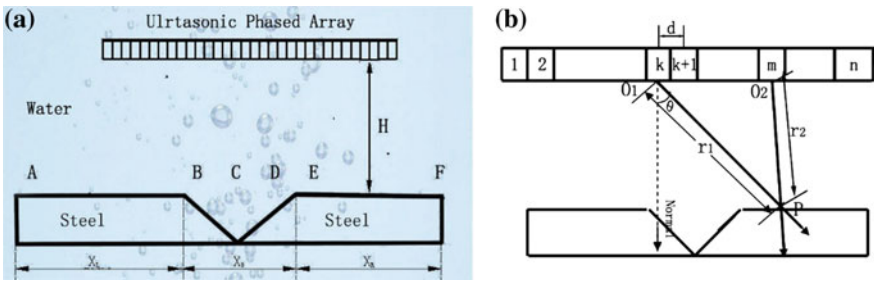

Fig. 1 Ultrasonic PA working method in wet welding

phase difference is an even multiple of π(180°), whereas it has the smallest amplitude when the phase difference is an odd multiple of π(180°). Then, the magnitude of the displacement of the summed waves is between the minimum and maximum values. As shown in Fig. 1a, PA is fixed above the welding material about 30 cm in water. Acoustic beams are sent out from the selected units with the same frequency at different moments according to the designed programs, so as to be focused exactly on the surface of workpiece in a line which is perpendicular to welding seam. By way of distance detection between PA and these convergences, material topography can be figured out and welding center for V-groove can be derived out. Compared with those of single-ultrasonic sensor, the detection speed and accuracy of PA can be improved greatly due to high working frequency and mechanical movement elimination.

The physical size of PA, the number of transducers, and the clearance between units have great effects on the focusing result. As described in Fig. 1b, let the beam be focused on the point P. The time interval between the elements O_1 and O_2 can be calculated out according to Cosine Theorem:

$$\begin{aligned} r_2^2 &= r_1^2 + [(m-k)d]^2 - 2r_1(m-k)d\,\cos\left(\frac{\pi}{2}-\theta\right) \\ &= r_1^2 + (id)^2 - 2r_1 id\,\sin\theta. \end{aligned} \tag{1}$$

From Eq. (1), time delay can be reasoned out as follows:

$$\Delta T_i = \Delta s/C = (r_1 - r_2)/C = \frac{r_1}{C}\left\{1 - \left[1 + \left(\frac{id}{r_1}\right)^2 - \frac{2id\,\sin\theta}{r_1}\right]^{\frac{1}{2}}\right\}, \tag{2}$$

where Δs is the difference of r_1 and r_2, C means the sound travel speed in water, and d is the interval spacing of adjacent units.

On the basis of Eq. (2), ArrayCalc is used to compute the interference patterns with a graphical method. In this software, individual array elements can be placed in 3D locations and orientations using a global coordinate system. A sphere centered on the global axis origin is the surface over which the array patterns are

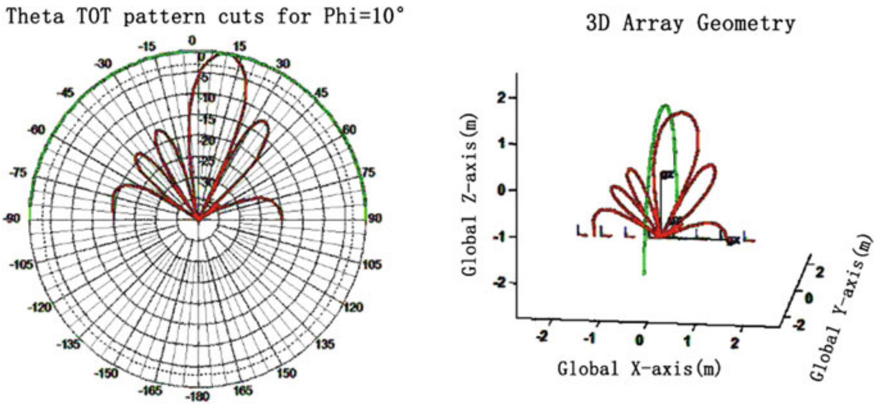

Fig. 2 PA focusing and deflection results

calculated. For a linear PA with eight elements, Fig. 2 gives out the interference results in 2D and 3D array geometry when the main lobe has a flexion of 10°.

Linear PA is selected here for wet welding, because this kind of PA is convenient to form a series of linear focusing points on workpiece surface than other shapes. Comparison tests are conducted to reveal the relationship between focusing precision and unit number with ArrayCalc which calculates the distance and direction from each element to the appropriate points on the surface and sums the field contributions to the interference patterns. For two different linear PAs with eight elements and 16 elements, besides 0.2 μs time resolution, other parameters are set as b = 2 mm and d = 3 mm. The focusing results are shown in Fig. 3.

More tests are carried out and some results are given out in Table 1. It is clear that more elements lead to better focusing accuracy, result in more converging strength, so concentrate more energy in main lobe. But in the meantime, more elements mean more channels, which can make circuits complicated and PCB board large.

At last, further research is carried out on relationship of time resolution and focusing accuracy. Beam deflection and focalization depend on time delay sequence. Erhard et al. [13] have pointed out that time quantizing error leads to discrete side lobe, which means energy expansion. The percentage of side lobe to main lobe can be expressed as [13]

$$S = \left(\frac{1 - \sin\frac{c}{\mu}}{N\,\sin\frac{c}{\mu}}\right)^{1/2} \approx \frac{\pi}{\mu(6N)^{1/2}}, \quad \mu \gg 1, \tag{3}$$

where N stands for the number of elements and μ is the ratio of pulse period time to minus quantized delay time. Small S value means better power concentration and high focusing precision. For a certain N, desired S can be achieved by increasing μ. In our study, the time delay is realized by hardware; that is to say, complex devices

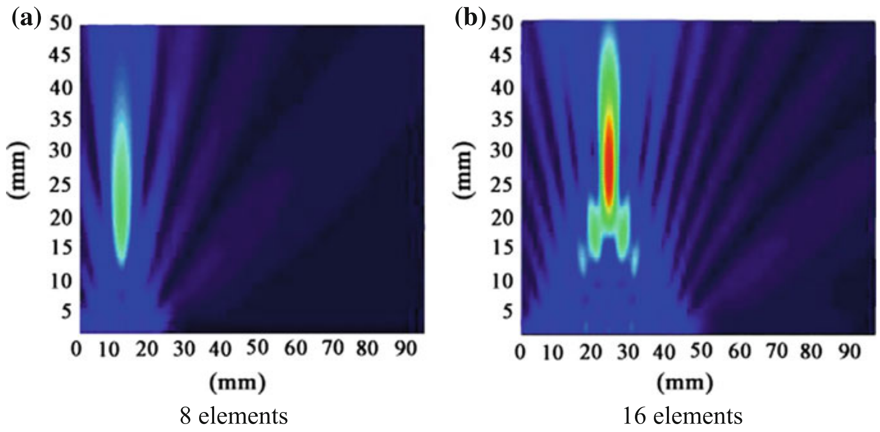

Fig. 3 Relationship between the number of PA units and the focusing precision eight elements, 16 elements

Table 1 Focusing accuracy under various number of elements

Element number	Ideal focusing point (mm, mm)	Real focusing point (mm, mm)	Mean square error (mm^2)
4	(5.5, 30)	(5.2, 16)	98.045
8	(11.5, 30)	(11.1, 20)	50.080
16	(23.5, 30)	(23.3, 27)	4.520
24	(32, 30)	(31.8, 28)	2.020
32	(47.5, 30)	(47.5, 29)	0.500

Table 2 Working parameters of PA

Number of elements	Center frequency (MHz)	Excitation voltage (V)	Gap of elements (mm)	Width of elements (mm)	Thickness of elements (mm)	Height of elements (mm)
16	2	120	1.7	1.5	1.1	10

are needed for high time resolution. Therefore, it is important to get the balance between circuit performance and focusing precision.

As for the working parameters of PA, sound propagation speed in water is roughly 1340 m/s, focal length is no more than 50 cm, and the minimum time interval is about 40 ns. It is proper to use a linear ultrasonic PA with parameters shown in Table 2.

3 Design of Electric Circuit

Besides generating and amplifying actuating signals, electric circuit is used to drive transducers according to specific time sequence, so that the sound beam can be sent out and echo can be sampled. The distance between PA and welding piece can be figured out by way of cross-correlation. The circuit used here can be divided into several parts, including control circuit, time delay sequence generator, stimulating signal amplifier, data acquisition unit, band-pass filter, wave sender and receiver, etc. It can be seen from Fig. 4 that control circuit contains 16 separate channels. Each channel has a triple-input control gate implemented by 74HCT11, which works in "AND" logic. Only when start, excitation signal and sequential signal are all in effective state simultaneously, the driven channel can become active, and the sound wave is emitted out.

Complex programmable logic device (CPLD), EPM1270144C5, provides high time resolution with a high-speed timer. It integrates 1270 logic units, 980 macro units, 212 users defined I/O pin, and 8192 bytes of flash memory in a single chip [14]. The steps for triggering each channel can be described as follows.

- Time values are sent to serial communication input buffer of CPLD from computer. The buffer is 8-bit long, and will be saved in turn to the registers of 16 transducers.
- A hardware accumulator starts to operate and compare the sum value with stored time. Time delay signal is sent out once the value matches.
- 74HCT11 is a high-speed controller with three input gates, i.e., sync signal ("start"), time delay signal (out1, out2, …), and actuating signal. Only when all the input signals are effective, the transducers can be driven.

PA is about 30 cm high above the welding piece. According to Eq. (2), the needed least delay time is 26.97 ns, and the max time is 1799.69 ns. By selecting

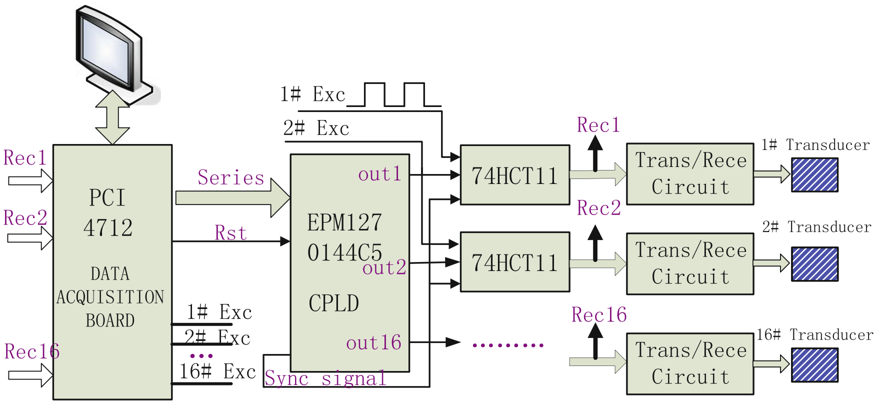

Fig. 4 Structure of control circuit

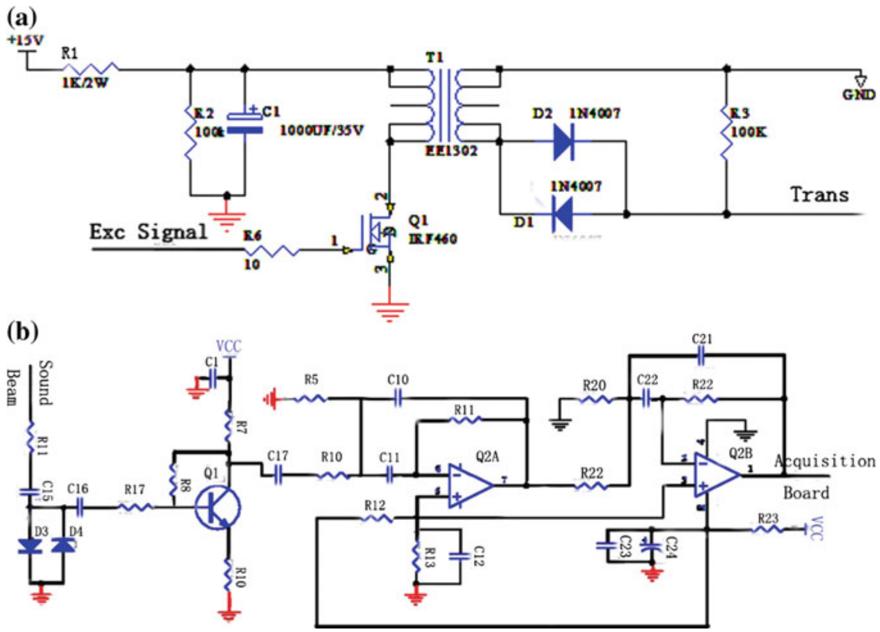

Fig. 5 Sound wave-emitting and receiving circuit

an 8-bit accumulator working at 100 MHz clock frequency, minimum 10 ns time delay and 2550 ns max delay can be attained with CPLD device, so this circuit can meet the resolution demand completely. But it should be mentioned that the initial time for each channel should be exactly same, and the wave frequency and original phase should be equal. To fulfill these requirements, high-frequency synchronization pulses are sent out from CPLD to ensure all the channels having the same original moment. Owing to the same inherent lag characteristic of channels, it can be guaranteed that the initial time for all the channels is entirely simultaneous.

Figure 5a is an emitting circuit. The exciting signal is amplified by the high-frequency transfer EE1302. The voltage can be risen to 130 V. The receiving circuit is shown in Fig. 5b. Echo waves are picked up by transducers, and then be enlarged by NPN9013. After that, they are adjusted by a band-pass filter which is constructed mainly by M33078. At last, the treated signal is provided to the data acquisition board PCI4712 for further processing.

4 Conclusion

In all, PA detects the distance by way of sound beam focusing. Its precision is mainly influenced by element number, element gap, and time resolution. Some conclusions can be drawn according to our study.

The focusing precision is closely related to the PA physical parameters and the number of elements. More elements lead to high accuracy.

The interferometry phase relies on the accuracy of delay time which is determined by time resolution, so the focusing precision is also related to time resolution.

High working frequency is useful for improving time resolution, which can be achieved with circuit based on CPLD in our research.

Further studies have carried out for PA to work as a sensor in wet welding. Results indicate that it can work in water conveniently, and the advantage of this sensor is remarkable.

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