

Development of the Phased Array System for Angle Beam Testing

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Abstract

The angle beam technique is commonly applied to ensure the quality of the welds. Usually this technique is manually performed, but recently the automatic ultrasonic testing instruments has been developed to decrease the inspection time and to increase the reliability. For this purpose, we have developed an array probes with a step shaped wedge. This system executes not only the angle beam technique but also the TOFD technique.

1. Introduction

The angle beam testing technique is commonly applied as a means for ensuring the quality of welds. Conventionally, this technique was performed manually. However, automation of ultrasonic testing instruments has increased reproducibility and recording of inspections. Multi-probe type apparatuses have mainly been developed for such angle beam testing devices¹⁾. Recently, however, there have been efforts applied to the development of so-called "phased array system apparatuses" to achieve higher inspection speeds and higher detectability²⁻⁶⁾.

Because it is possible to replace the conventional mechanical probe scanning method on the angle beam testing to an electrical scan called a linear scan, inspection times have been dramatically shortened. Furthermore, the angle of incidence using a sector scan is controllable, enabling a flexible and highly precise scan. However, this method was developed for use in the practice of medicine and has yet to find wide use in industrial applications.

Thus, a 256 channel phased-array pulser/receiver prototype that uses wedge-shaped array probes applied in angle beam testing was developed. This system comprises a high speed and flexible phased-array technique and simultaneously executes TOFD (Time Of Flight Diffraction) to quantitatively evaluate the height of defects. This is a system for an angle beam testing technique that uses a phased-array method and for synthesized analysis of the results of the TOFD technique.

2. Phased Array Ultrasonic Testing System

2.1 Array probes

The shape of an array probe for angled beam testing is a product of a normal angled probe. As shown in **Fig. 1**, a prototype with a wedge-shaped linear array probe was developed⁴⁾. This type of phased array system is quite applicable to high speed testing because it electrically scans in the direction perpendicular to the welds. Also, the angle of incidence of ultrasonic beams is variable and its ultrasonic beams can be focused in the plate thickness direction. However, in this method a difference in sensitivity is caused by the difference of length of the wedge in left side and right side. The correction of attenuation is needed to synthesize received waves.

A wedge-shaped array probe as shown in **Fig. 2** was developed⁶⁾. Using this method, the distance in the wedge from each element to the irradiating point is kept at a constant, thereby eliminating the

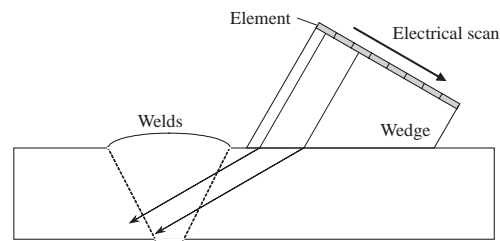


Fig. 1 Shape of array probe for general angle beam testing

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need for correction of attenuation. Furthermore, it is possible to increase the number of channels employed therein.

In order to widen the scope of variability of the angle for ultrasonic beam irradiation, which is an essential feature, when developing the method of array probing, it was necessary to provide a wide-enough ultrasonic beam that is emitted from each element. Thus, to determine the size of each element, the sound field of an ultrasonic beam was calculated, as shown in Fig. 3, when varying the width of elements in the electrical scanning direction. Shown in Fig. 3, at a location near 30 degrees, the sound field of shear wave varies around the critical angle of longitudinal wave. Sound fields are wide enough if the width of the element is set to approximately 0.7 mm. It was also found that it was possible to hold down sound pressure decreases near the critical angle of longitudinal wave to within 6 dB.

If the width between the elements is 0.7 mm in the electrical scanning direction, and the vertical direction element width is set to 10 mm which is the same as normally used angle probes, elements with a fine angle of 0.7×10 mm for only the number of channels must be mounted in a step-wedge shape to manufacture a step-shaped array probe. Due to variations in the manufacturing process, it is difficult to maintain the angle between each element. Thus, an array probe structure equipping two elements per level in a wedge-shape was developed, as shown in Fig. 4. Element dimension on the prototype array probe: 0.7×10 mm; Design angle: 62 degrees; Frequency: 5 MHz. There are 64 channels of elements. Fig. 5 shows the prototype array probe.

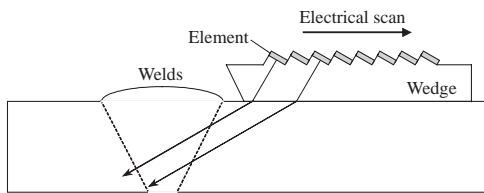


Fig. 2 Shape of wedge-shaped array probe

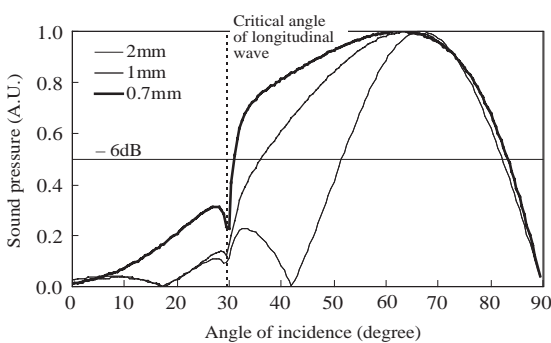


Fig. 3 Variation in sound field according to element size

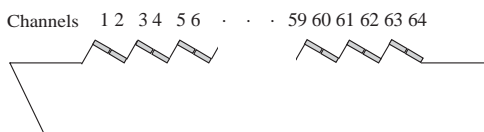


Fig. 4 2 linked wedge-shaped array probe

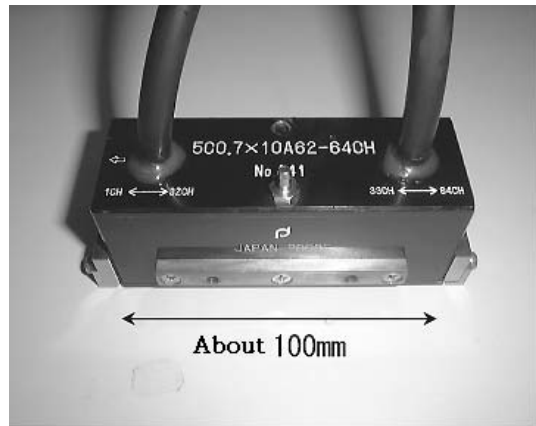


Fig. 5 Prototype array probe

2.2 Phased array method test system

The configuration of the phased array method inspection system is shown in Fig. 6. Fig. 7 is an external view. This system has 256 channels for sending and receiving ultrasonic signals. Electrical scanning condition settings and scanning controls are all performed by a PC. The design is considered based on the actual field inspection. For example, the scanning unit and pre-amp are connected by an approximately 30 meter cable. Also, there are also a pair of angle probes that can be mounted. The configuration shown in Fig. 6 shows the mounting of the a longitudinal wave angled probes for TOFD.

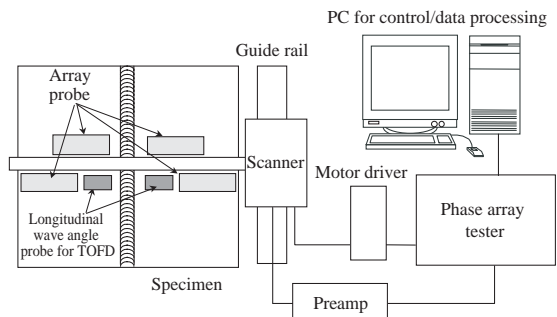


Fig. 6 System configuration

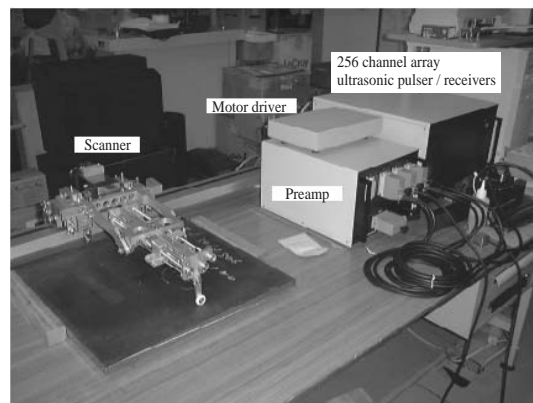


Fig. 7 External view of developed system

Table 1 Main specifications of the phased array pulser/receivers

Pulser/receivers	
No. of Channels	256
No. of Simultaneously driven channels	16
Delay time	0 to 22 μ s
Units for delay time variation	5 ns
Pulse amplitude	400 to 50V
Pulse rise time	10 ns
Maximum gain	80 dB
Band width	3 to 7 MHz
A/D Converter unit	
Sampling rate	100 MHz
Resolution	16 bit

This system is capable of compound testing. Specifically, this system employs both the pulse-echo technique using the array probes and the TOFD technique that applies the longitudinal wave angle probes. See Table 1 for details on the specifications for the phased array testing apparatus.

3. Phase Control Technique

The direction and convergence of the synthesized ultrasonic waves are controlled by adding a delay time to the pulse that is charged to each element on the phased array technique scanning system. This is called phase control. The method used for calculation of this delay is very important to effectively control the ultrasonic waves. The method used for calculating delay time for the step-shaped array probes is described.

The angle of incidence of the ultrasonic beam is θ ; and the depth of convergence is D . Also, the number of simultaneously driven elements is $2N$; the wave velocity of sound in the wedge material is C_1 ; and the wave velocity of sound in the target specimen is C_2 . The point, where the line drawn in Fig. 8 from the center of the simultaneously driven elements at the angle of incidence α in the wedge meets the boundary with the target specimen, defines the origin of the X and Y axes. The angle of incidence in the wedge α is calculated using Snell's law from the angle of incidence θ .

$$\alpha = \sin^{-1} \left(\frac{C_1}{C_2} \sin \theta \right) \quad (1)$$

If the height from the boundary surface to the center of the element is h , and the pitch in the X direction is p , the following equations are true for the coordinates of the center of the elements (for x_i and y_i).

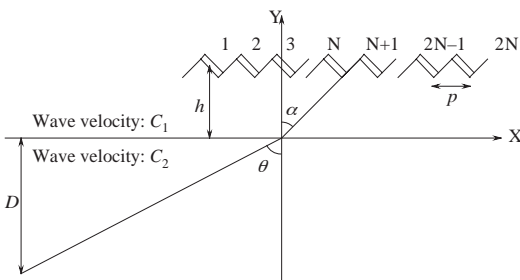


Fig. 8 Geometric arrangement of elements

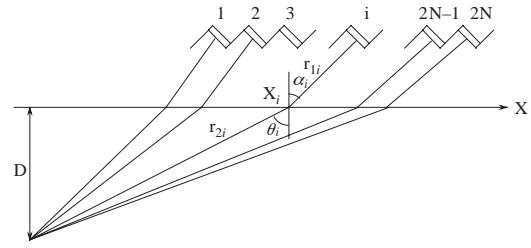


Fig. 9 Delay time calculation method

$$\begin{aligned} x_i &= h \sin \alpha - (i - N)p \\ y_i &= h \end{aligned} \quad (2)$$

To calculate delay time, the beam path from the convergence point to each element is calculated. This is depicted in Fig. 9. To make the calculation easier, the ultrasonic beam emitted from an element is considered to advance as a single direct line. Thus, if the X coordinate at the point where the beam intersects the boundary surface, following equation is obtained by Snell's law.

$$\frac{\sin \alpha_i}{C_1} = \frac{\sin \theta_i}{C_2} \quad (3)$$

It is possible to calculate the value of X_i from the geometric conditions:

$$\begin{aligned} \tan \alpha_i &= \frac{x_i - X_i}{h} \\ \tan \theta_i &= \frac{x_i + D \tan \alpha}{D} \end{aligned} \quad (4)$$

and

Accordingly, the path of the beam in the wedge and in the target specimen will be:

$$\begin{aligned} r_{1i} &= \sqrt{(x_i - X_i)^2 + h^2} \\ r_{2i} &= \sqrt{(x_i - D \tan \alpha)^2 + D^2} \end{aligned} \quad (5)$$

Therefore, the beam delay time t_i from the point of convergence point to each element is found using the following equation.

$$t_i = \frac{r_{1i}}{C_1} + \frac{r_{2i}}{C_2} \quad (6)$$

Actual delay time for each element is applied with the difference to the maximum value of those t_i .

4. Results of Experiments

4.1 Sound field evaluation of a prototype array probe

A jig that can move the electro magnetic acoustic transducer for the shear wave along the 100R surface of the STB-A1 test piece was manufactured. With the configuration shown in Fig. 10, the directivity of a transmitted ultrasonic wave beam is measured.

Fig. 11 shows the results of measurements using a tested array probe setting the angle of incidence at 60° and 65° according to the phase control, and the results of numerical calculations⁷⁾. The angle of the ultrasonic wave beam that was generated according to the phase control was substantially as set, and thus the appropriateness of the

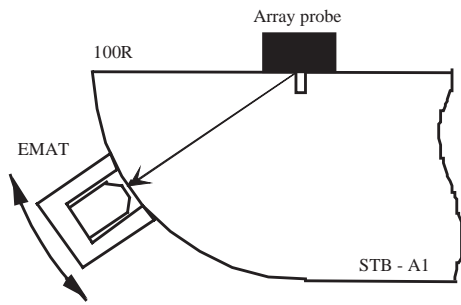


Fig. 10 Directivity measurement method using EMAT

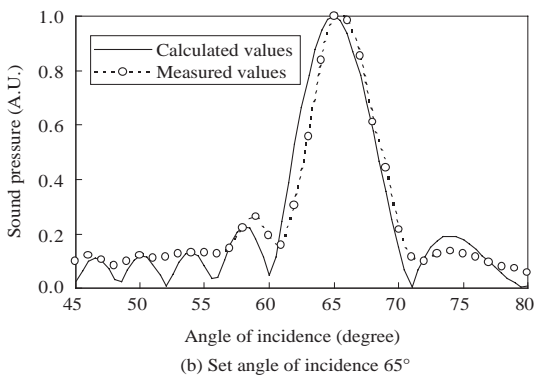
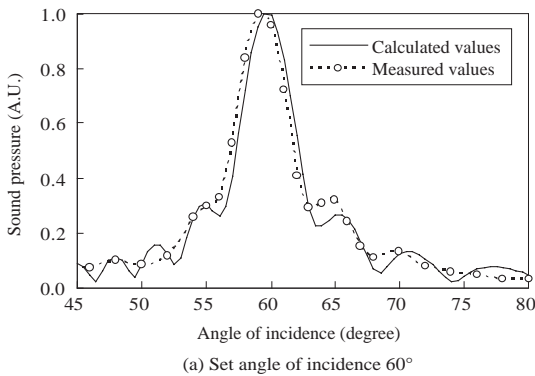


Fig. 11 Comparison of EMAT measurement results and calculated values

phase control as described in section 3 was verified. Furthermore, the actual measurements of the sound field matched the results of the numerical calculations well.

4.2 Results of the flat plate test specimen

In a 19 mm thick steel plate material, a V cut of 60° was applied, and to the excessive welding at a central location on welded specimen vertical holes of 2.4 mm and 3.2 mm were produced. Slits were made in the sides of the excessive welding at the backside. The slits were 0.5 to 1.5 mm deep and 10 mm long. One 64 element array probe was used for the tests. Of those, 16 elements were driven simultaneously and signals were sent and received for phase control so that the testing angle would be 60°. Therefore, 49 tests were executed in the welding line and in the vertical direction with one electrical scan.

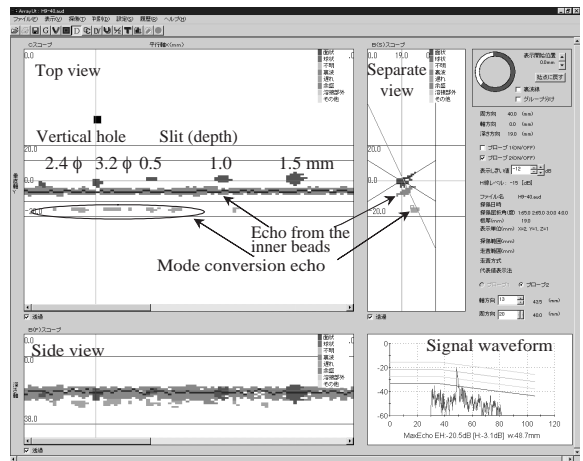


Fig. 12 Results of flat specimen

The results of the tests were displayed as images as can be seen in Fig. 12. It is clear that the slits at a depth of 0.5 mm were detected. Along with the echo present from the defects at the angle test of the welded portion, echoes from the excessive welding at the backside (backside wave echo) and mode conversion echoes were detected. However, this was recognized semi-automatically on the developed system to enable color coded display for each type of defect.

4.3 Results of the steel pipe welds

Tests were performed on the circumferential weld portion of an X-65 steel pipe (diameter: 600 mm; thickness: 16 mm). Specimens with several welding defects (blow holes, lack of fusion, incomplete penetrations) were produced. Fig. 13 shows the status of the test; Fig. 14 shows a portion of the test results. Fig. 14 shows an image of TOFD instead of a side view. However, it is clear that both the pulse-echo technique and TOFD technique were able to detect blow holes and the lack of fusion. By executing inspections that employ both of these techniques, it is possible to realize both the compatibility to conventional inspections using the pulse echo technique and quantitative analysis according to the TOFD technique.

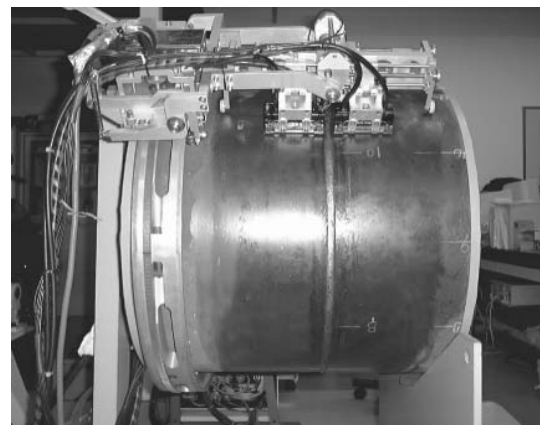


Fig. 13 Status of steel pipe test

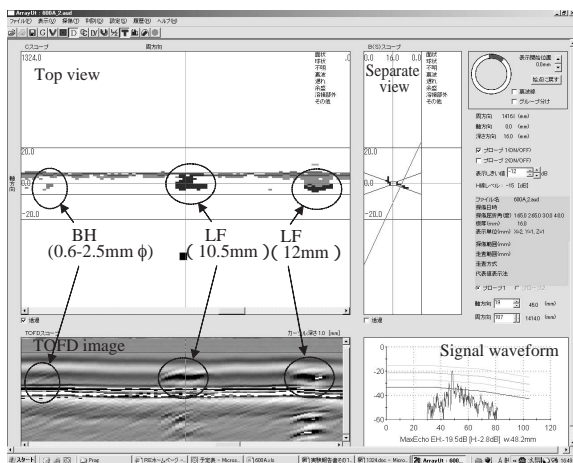


Fig. 14 Results of steel pipe welding (partial)

5. Conclusions

A phased array system for angle beam testing that uses array probes with a wedge-shape. This method uses electrical scanning to

not only to enable high speed testing, but also to vary the angle of incidence of the ultrasonic beam. Because of these characteristics, this system flexibly handles differences in setting angles for testing for such materials that have acoustic anisotropy. Furthermore, the developed system maintains the compatibility with conventional inspections when both angle beam testing using the phased array technique and the TOFD technique according to the longitudinal wave angle probes mounted separately, are executed simultaneously. This system comprises superior and highly precise measurements of defect heights.

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