Study of PA-TOFD Inspection based on Numerical Simulation

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Abstract. Time of flight diffraction (TOFD) technique and phased array ultrasonic testing (PAUT) have been developed rapidly in the last decades. They have shown the tendency to replace traditional volumetric weld inspection techniques, such as radiography and pulse-echo ultrasonic testing. The TOFD inspection with sector scan phased array not only retained the high positioning accuracy of TOFD technique, but also obtained higher detection sensitivity over the entire range of test piece thickness. In this paper, the model of a 48.0mm thick carbon steel weld was established, in which the depth of defects was from 2.0mm to 46.0mm and the height was from 1.0mm to 3.0mm. The TOFD technique combined with sector scan phased array method, i.e. PA-TOFD, was simulated based on the model with CIVA software. A series of TOFD D scanning images under different sector scanning angles were obtained and analyzed in one run. The echo amplitude and the positioning accuracy of defects measured by PA-TOFD method were compared with that of conventional TOFD technique respectively. Result shows that the PA-TOFD method can accurately determine the depth of defects by extracting the defect signals at favorable angle, and the defects with different depths can achieve higher echo amplitude. This method has the advantages of phased array technique, such as beam steering, energy focusing, as well as the high positioning accuracy of TOFD technique. It is significant for improving the reliability and efficiency of weld detection.

1. Introduction

Time of flight diffraction (TOFD) technique and phased array ultrasonic testing (PAUT) are two kinds of superior nondestructive testing techniques in weld inspection. Whereas, TOFD technique which relies on the diffraction signals to detect defects, has a high quantitative precision up to ± 1mm in the thickness direction of welds. Traditionally, the TOFD technique is done in a pith-catch arrangement using single element transducers\(^{(1)}\). The probe size is small and the beam angle is large. This results in an uneven distribution of acoustic field energy and a low detection rate of near surface. Therefore, it usually need zonal discrimination for weld thicker than 50 mm\(^{(2)}\). While for PAUT, by controlling the exciting time of individual crystals, it allows dynamic beam steering and energy focusing, and can achieve a better ultrasonic beam detectability and efficiency. Some researches have shown that combining PAUT and TOFD technique will result in a more robust and flexible inspection technique\(^{(3-5)}\). But most of these researches just performed PAUT and TOFD simultaneously. The two methods were combined formally, in which multiple groups of
phased array probes and TOFD probes were clamped on a scanner, but the phase array data and TOFD data were acquired and analyzed respectively. The PA-TOFD method mentioned in this paper, refer to using multi-element probes to perform TOFD inspection, that is two arrays of piezoelectric crystals being held together just like a regular TOFD setup but allowing steering and/or focusing of the beam in many directions by setting different focus laws. The development of hardware and software has made it possible to conduct PA-TOFD inspection. Experiment of PA-TOFD method on 20mm thick steel plate has been carried out by BRILLON of Olympus[6]. The results showed that a single PA-TOFD inspection with sector scan was equivalent to multiple scans of conventional TOFD inspection with different incident angles. A further study of PA-TOFD inspection was conducted in this paper with CIVA software.

![Fig. 1. Schematic diagram of PA-TOFD setup and ultrasonic line distribution.](image)

**2. PA-TOFD Basics**

Fig. 1 shows a typical PA-TOFD setup. Two multi-element probes were involved to generate beams in opposite directions, in which one was for transmission and the other for reception. TOFD relies on the difference of propagation time between lateral wave and diffraction wave to resolve the position and size of the indications. The depth $d$ of a point indication could be given by Eq.1

$$d = \sqrt{(ct)^2 - s^2}$$

where $t$ is the time of flight of the signal from the exit point of the probe to the defect, and is also the time taken by the signal, after diffracting off that defect to reach the receiving probe. $2s$ is the distance separating the index points of the probes which is also called the probe center separation (PCS) and $c$ is the velocity of the sound wave (mainly compression wave). The inspection principle of PA-TOFD method is still based on this, but the difference is that the PCS varies with beam steering and focusing, which causes incident point shift. To avoid the error of positioning, the PCS should be calibrated with incident angle.

In the inspection of PA-TOFD based on sector scan, a pseudo S-scan image and several D-scan images under different sector scanning angles were obtained in one run. By changing the scanning angle, the detector can extract defect signals at favorable angle to detect the size and depth of the defect.

**3. Simulation**

3.1 Model of Simulation

A model of 48.0mm thick carbon steel weld, which has a density of 7.8g/cm$^3$ and a longitudinal wave velocity of 5900m/s, was built with CIVA. It contained 3 surface notches, 6 cracks and 2 bottom notches. All the defects were 16.0mm in length. The model is shown as
The location and sizing information of defects is depicted in Table 1. (Three surface notches were 1.0 mm, 2.0 mm, and 3.0 mm in height, respectively. Three cracks were 12.0 mm in depth and 1.0 mm, 2.0 mm, 3.0 mm in height, respectively. The other three cracks were 36.0 mm in depth and 1.0 mm, 2.0 mm, 3.0 mm in height, respectively. Two bottom notches were 2.0 mm, 4.0 mm in height, respectively).

Fig. 2. Schematic diagram of weld model and defects distribution.

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<td>/</td>
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The simulation results of PA-TOFD method performed on the above weld model with CIVA 11.1 were compared with that of TOFD technique. The 60° longitudinal probes with a nominal central frequency of 5 MHz were used in both PA-TOFD and TOFD inspections and the PCS measured under 60° was 111 mm. The difference is that PA-TOFD used 32 elements linear array probes with a nominal central frequency of 5 MHz, and the sector scanning angles were set varying from 55° to 85° with a 5° step.

3.2 Result of Simulation

Fig. 3 and Fig. 4 show the simulation results of TOFD technique and PA-TOFD method respectively. The calibration reference in amplitude corresponded to the 1.0 mm high crack echo located at 36.0 mm depth obtained during the inspection with 60° incident angle. The gains of the two inspection images were both set to make the calibration amplitude reach 100% full screen height. This offered a uniform datum to further comparative analysis on the two inspection methods.

Only a D-scan image was acquired in TOFD inspection, presented in Fig. 3, in which the 12.0 mm depth and 36.0 mm depth cracks were easy to distinguish from the background, but the near surface defects were hard to detect. In PA-TOFD inspection, corresponding to each scanning angle, a D-scan image was acquired. Fig. 4 enumerated the pseudo S-scan image and D-scan images corresponding to that of 60°, 75°, and 85° condition. When the steering angle was smaller (α=60°), as seen in Fig. 4(b), the bottom notches were easy to
detect, while when the steering angle was larger ($\alpha=85^\circ$), as seen in Fig. 4(d), the surface notches were easy to detect.

![Fig. 3. D-scan image of TOFD, f=5MHz, $\alpha=60^\circ$, PCS=111mm.](image)

![Fig. 4. Pseudo S-scan and D-scan image of PA-TOFD, f=5MHz, PCS=111mm, $\alpha=60^\circ$, 75°, 85°.](image)

Fig. 5 illustrated the contrastive analyses of amplitudes from the echo signals measured by traditional TOFD technique and PA-TOFD method respectively. Normalization processing was applied to echo amplitude, so the amplitude in Fig. 5 is a decibel value. The normalizing amplitude was determined by amplitude of defect $q_7$ (1.0mm height, 36.0mm depth). Wherein, the amplitude of each defect in PA-TOFD inspection was measured at a favorable angle. Also, the amplitude of the defect $q_5$ (4.0mm height surface notch) was 24dB higher by PA-TOFD method than that by conventional TOFD technique. It was true that rather high detection sensitivity over the entire range of test piece in the thickness direction can be obtained by adjusting angles $\alpha$ in the PA-TOFD method.
Fig. 5. The comparison of defect amplitude between PA-TOFD and TOFD.

Fig. 6 illustrated the variation of the PCS values with sector scanning angle in PA-TOFD inspection under the parameters mentioned above. After calibration to PCS, the position errors of both PA-TOFD method and conventional TOFD technique were measured (see Fig. 7). It was obvious that the positioning precision of PA-TOFD method was nearly the same as TOFD technique, the maximum error of which was just 0.7mm.

Fig. 6. PCS corresponding to scan angle in PA-TOFD inspection.

Fig. 7. Positioning error of PA-TOFD and TOFD.
4. Conclusion

Preliminary study of PA-TOFD method based on sector scan has been performed with CIVA software in this paper. The results revealed that the PA-TOFD method could not only maintain the advantages of high positioning accuracy of TOFD technique in the thickness direction but also obtain high detection sensitivity over the entire range of test piece. According to the research on the PA-TOFD method based on sector scan phased array, it is prospected that quantitative accuracy determined on defects in both welding line direction and thickness direction can be further increased by setting beam focusing. Consequently, the PA-TOFD method retains the advantages of TOFD technique while overcomes the disadvantages on some very aspects. It’s a method that can acquired more detailed information in one run, and should be significant for improving the reliability and efficiency of detection.

References