17th World Conference on Nondestructive Testing, 25-28 Oct 2008, Shanghai, China

TOFD Inspection with Phased Arrays

Charles BRILLON [1], Tim ARMITT [2] and Olivier DUPUIS [1]

[1]Olympus NDT Inc.
505, boul. du Parc-Technologique, Québec, QC, G1P 4S9, Canada
E-mail : charles.brillon@olympusndt.com, olivier.dupuis@olympusndt.com

[2]Lavender International NDT Consultancy Services Ltd.
Unit 7, Penistone Station, Sheffield, S36 6HP, UK
E-mail : tim@lavender-ndt.com

Abstract

In the last decades two major technologies changed the face of ultrasonic NDT viz., time of flight diffraction (TOFD) and phased array ultrasonic testing (PAUT). When used in conjunction, these two techniques allow for higher probability of detection (POD), normally requiring a great amount of time and/or experienced UT inspectors. To do TOFD however (even TOFD by itself), it is necessary to have different sets of probes with different probe separations when one wishes to inspect very thick materials.

With the advent of more sensitive transducer arrays and faster electronics, we can now envisage, using multi-element probes, to perform multiple TOFD inspections (the different apertures, offsets and refracted angles all being changed electronically) in one run and with a minimum number of props. These different TOFD scans may also be merged *a posteriori* so that a simple global picture finally emerges from the acquired data.

In this paper we will present some results achieved with this method as well as both theoretical and practical aspects of the problem.

Keywords: Phased array, TOFD, sizing

1. Introduction

The TOFD technique was developed in the 70's [1]. It was devised as a tool for accurately sizing and monitoring defects. Indeed, since Pulse-Echo (PE) techniques allow for sizing based on amplitude of the reflected signal, it is very much dependent on the orientation of the defects. A slight change in angle from normal reflection can induce a large error in the size or can result in the defect being missed altogether. TOFD on the other hand works with diffracted signals and can spot defects no matter what their orientation. It is pretty robust as far as the skew of the probes is concerned.

In this paper we show that PAUT traditionally used with PE techniques can be used to perform more complete TOFD scans by allowing dynamical steering of the UT beams.

2. TOFD Basics

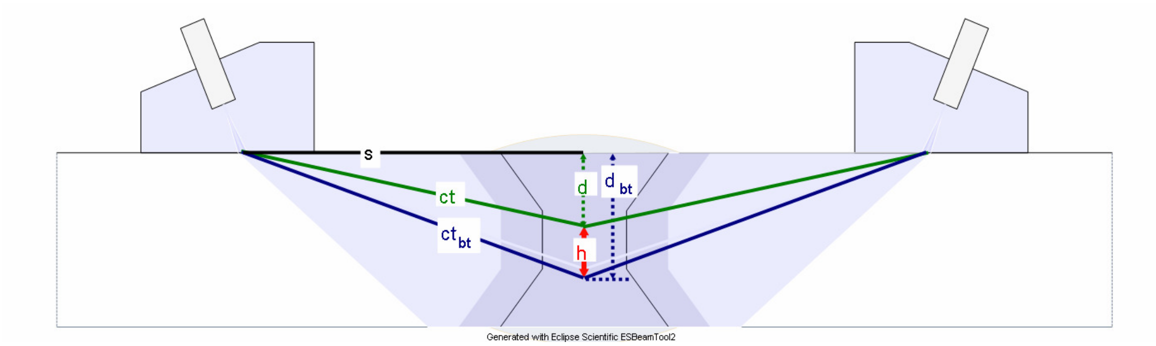

Figure 1 This figure illustrates a basic TOFD setup. A pulse leaves the probe on the left. The beam spreads (illustrated in grayish blue) and diffracts off the defect with two different times. Assuming this defect is positioned in the center of the weld, we can deduce its height and depth from the resulting A-Scan

TOFD relies on the sole diffracted signals inside a material to resolve the position and size of the indications. Figure 1 shows a typical TOFD setup. The depth ***d*** of a point indication will be given by

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

Eq. 1

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 (most of the time a compression wave) inside the material.

3. Obstacles and sources of error

TOFD is a very powerful tool but is not perfect. In this section we list some of the main weak points of TOFD. [1]

- **Timing errors**

  For a given error ***Δt***, the error on time precision in an A-Scan, the error on depth grows with the attacking angle and the pulse width (indirectly the frequency of the probe).

- **Lateral wave dead zone**

  Since the lateral wave (LW) has an extension in time and is present on every A-Scan (if there is no surface breaking defect), it will potentially hide any signal appearing in that time window. This is the so-called lateral wave dead zone.

- **Off axis errors**

  In section 2, we assumed that an indication was positioned in the center of the weld. In fact, in most cases this is not true: defects like lack of sidewall fusion (LSF) will be located on the side of a weld bevel; and cracks have different orientations. There will thus

[1] For more information see for instance reference [2].

be an error on the position depth, as well as an intrinsic error on the lateral position of the of the defect.

- **Resolution errors**

  Because of the effective extent of the pulse in the material it is sometimes very difficult to resolve the height of defects.

4. Solutions with phased arrays

All of the problems encountered above have a common solution: vary the parameters in order to get the best possible coverage. This is done by performing multiple scans. This is where phased arrays come in handy. A transducer array is comprised of many single element transducers.

In phased arrays, the individual crystals are excited at different times. This creates a constructive interference that allows steering and/or focusing of the beam in many directions. Delays are usually also applied when receiving the signal to make sure that the maximum energy possible is displayed in the A-Scan.

Phased arrays are mostly used in PE mode. They can also be used in *through transmission* mode (one probe on the OD and one probe on the ID) or the so-called *tandem mode* (to detect vertical flaws via skips off the bottom of a piece). However, they are seldom used to detect diffracted signals, which are rather faint.

4.1.Sectorial TOFD

In TOFD, a sectorial scan can be used to focus at different depths in the weld. Two arrays of piezoelectric crystals are held together just like in a regular TOFD setup. One of the probes emits beams at different angles. In Figure 2 we have four. Thus, the four quadrants on the right-hand side of the image represent one of the four beams illustrated on the End View on the left-hand side.[2] The Side Views on the right-hand side have already been calibrated on the lateral wave and the back wall.

If we follow the defects at the top (number 1) and the bottom (number 2) of the plate, we notice that the top one becomes more and more visible as we increase the angle. This is because there is more energy to hit it at those higher angles.[3] Speaking of the lateral wave, even though it is not very well defined, we can see it "penetrates" the material a lot, whereas for other angles it is shorter. The lateral wave extent depends on the pulse width and on the PCS. Assuming that our PCS is constant, we conclude that the pulse width is changing. Actually, the dominant frequency is lower for the lateral wave in that area.[4] Defect number 1, which was hidden below the lateral wave, then becomes apparent when the angle increases. Defect number 2, on the other hand, disappears when we increase the angle: not enough energy is reaching the bottom of the plate.

2 This view is just a guide to the eye and there is no point in trying to make sense of the real measurements (index or ultrasonic) on that part.

3 You can see that the software gain had to be cranked up a lot in order to pick up the lateral wave for lower angles.

4 In fact, a fast Fourier transform (FFT) of the lateral wave for the 40 degrees beam gives a dominant frequency of around 1.91 MHz (we get around 3.9 MHz for the 70 degrees beam) because of the beam spread which is wider for low frequencies.

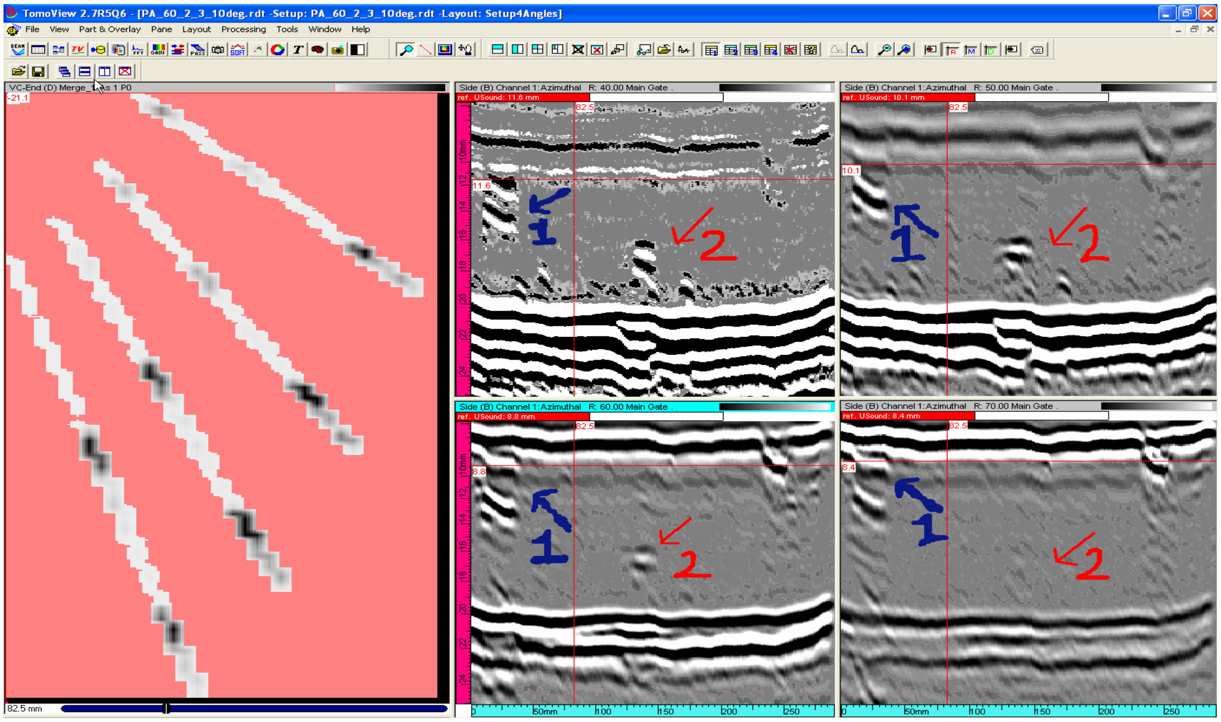

Figure 2 Sectorial beams. 10 degrees apart. PCS constant. Beam focused at different depths. There are four angles: 40-50-60-70 degrees, with their B-Scans on the right-hand side, respectively in the top left, top right, bottom left and bottom right quadrants. The blue arrow points to an indication, labeled "1" (probably a lack of fusion), while the red arrow points to another one, labeled "2". The scans were performed and viewed with the TomoView™ software by OlympusNDT® on a 20 mm thick steel plate (5.9 mm/µs). 5MHz probes. With a maximum aperture of 16 elements were used.

For the purpose of demonstration, we used only four beams, but we could have put many more (for instance one beam for every degree). Doing so, we are sure to hit the whole weld bevel with optimum frequency and intensity. In fact, nothing prevents the use of the "power" of phased array to focus the beam (using Huygens' Principle) along a vertical line in the middle of the weld.

4.2.Varying the PCS

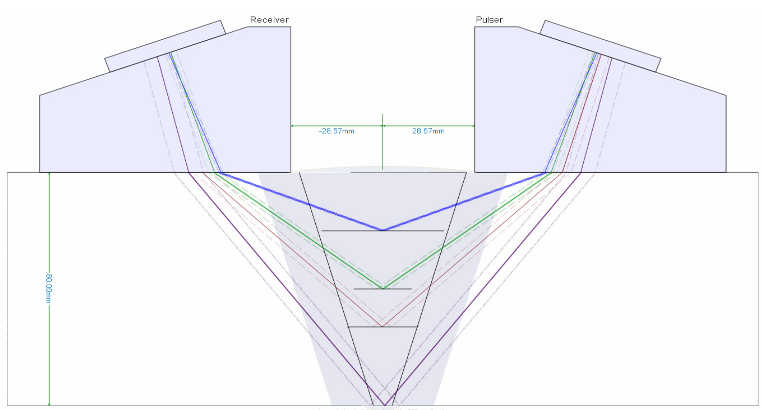

Figure 3 Illustration of varying PCS to better cover the weld center. 5L64-A2™ probes by OlympusNDT® have been used. As the focus is set deeper the VA of the probe is increased for more intensity.

Instead of using a sectorial scan, the same angle can be used but we can vary the PCS electronically (see Figure 3). This is done by using a linear scan with an angled wedge, the exit point of the beam changes with the fired beam position. The receiving probe will have symmetric electronic movement so ***s*** will be the same on both sides of the weld center. Here, we have a combination of linear and sectorial scanning.[5] One can notice that the PCS is dynamically changing for each beam (just below the probe and before entering the shoe).

4.3. Raster TOFD

So far, we have concentrated our efforts on varying the PCS and beam angles dynamically to have better response and resolve defects more efficiently. One last aspect we have not yet covered in this section is the depth error due to off-axis positioning of defects. The conventional method to do this is to perform a parallel scan on a defect. With long enough arrays, this can be performed dynamically, as can be seen in Figure 4.

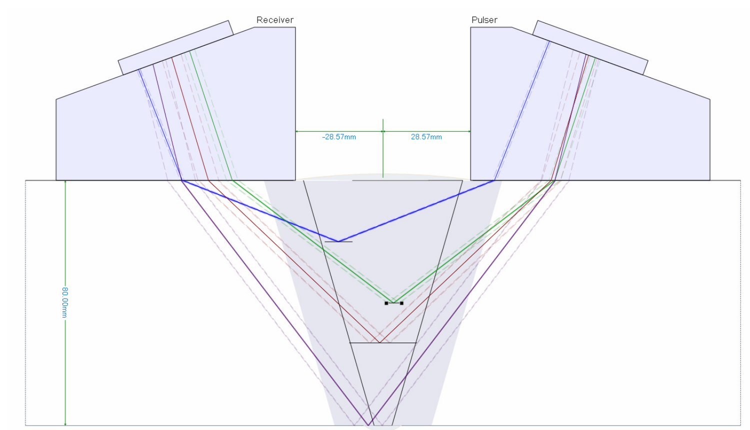

Figure 4 Illustration of TOFD rastering scan. 5L64-A2™ probes by OlympusNDT® are displayed. An electronic sweeping effectively reproduces the results obtain with a mechanical parallel scan.

The setup from last section (Figure 3) is used again. This time the PCS is kept constant. The true depth of the indication will then show up as the minimum position on an End View. The offset of the defect will be given by the index offset of the focal law which picked up the minimum position.

5. Other considerations

5.1.Merging the data

Performing all these scans in one pass will generate a huge amount of data. In PA softwares like TomoView™ it is possible to merge the data that is redundant (like when sectorial scans are overlapping for instance). The image below (Figure 5) shows a mere view of the data acquired in Figure 2. The image is not scaled but the idea is there. Now this would represent a Side View (i.e. for a single index value). With the rastering it is possible to obtain several values of index for the entire volume of the weld. Basically, we obtain a volumetric TOFD view.

5 Different angles are being used but this is to better cover the whole piece (keeping only one angle and varying the PCS will give us only limited focused coverage of the center of the weld.

We can also note that at a fixed scan axis position value for the probes, the merging of the data is not really influenced by the variation of the couplant thickness. Therefore, there is no need to synchronize the lateral wave like we sometimes need to do with perpendicular scans.

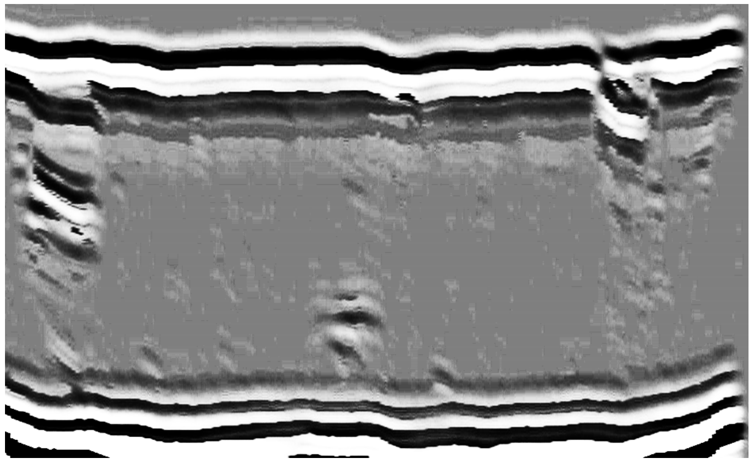

Figure 5 This is a merged view of the data displayed in Figure 2. Courtesy of NSG® Japan.

5.2. Comment on probes

Probes used for TOFD in PA should be made of traditional piezo-ceramic elements. Their main advantage is that they can be dampened more easily than other types of probes. It is then easier to select the right amount of damping material in order to find the appropriate pulse for top and bottom tip resolutions as well as minimum extent of the lateral wave.

6. Conclusion

It has been found that PAUT techniques can be used with TOFD with little modifications. A PA-TOFD system has all the forces of regular TOFD but few of its weaknesses. It allows for better localization of defects and everything is done in one pass and kept in one data file. Sectorial scans and linear scans can be combined and merged *a posteriori* to better analyze the data at hand and in a more user-friendly fashion. No call to rescan a certain area needs to be made–the system does it all in one pass. The problem of the lateral wave extent can be optimized by finding the right pulse: finding the right probes with the right damping is thus really important.

Acknowledgments

Charles Brillon would like to thank the people at Lavender's International for their hospitality while part of this work was performed. Special thanks go to Tim Armitt, Steve Hewling and Nicola Dodsley.

Bibliography

[1] Silk, M.G., "Sizing crack like defects by ultrasonic means", in Research Techniques in Non-destructive Testing, vol. 3, ed. by R.S. Sharpe, Academic Press, London, 1977.

[2] Silk, M.G., “An evaluation of the performance of the TOFD techniques as a means of sizing flaws, with particular reference to flaws with curved profiles”, Insight, vol. 38, pp. 280-287, 1996.