INSPECTION USING SHEAR WAVE TIME OF FLIGHT DIFFRACTION (S-TOFD) TECHNIQUE

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ABSTRACT: Ultrasonic Time of Flight Diffraction (TOFD) for sizing defects is based on the time of flight of the longitudinal diffracted echo(es) that is (are) generated when a longitudinal wave is incident on a crack tip. TOFD technique so far has been commonly applied for the inspection of thick sections (>15 mm) and thickness below 5 mm from the scanning surface. This paper focuses the applications of the TOFD technique to thin and near surface inspections using shear wave diffracted echo (es) from the defect tips. Experimental result for simulated and realistic defects in thin samples will be presented.

Keywords: TOFD, thin sections, S-TOFD, diffraction
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INTRODUCTION

Conventional ultrasonic technique uses the pulse transit time to locate and the echo amplitude to size the flaw. For accurate flaw sizing, the amplitude of the back reflected wave may not always be sufficient, since the amplitude of the reflected pulse may be influenced by many parameters other than the size of the reflector. Such parameters include the surface roughness, transparency and orientation of the defect. In order to ensure a more reliable defect sizing ultrasonic NDE technique, the TOFD method was developed [1-7].

When an ultrasonic wave is incident on a crack-like defect, the wave is reflected, transmitted, and also diffracted at the edges. The diffracted energy spreads over a wide angle and can be picked up from almost anywhere along the surface of the structure. The defect sizing method based on the measurements of time difference between the diffracted signals from the crack tips (edges) is called Time of Flight Diffraction (TOFD) method. The basic principle of TOFD has been illustrated in Figure 1.

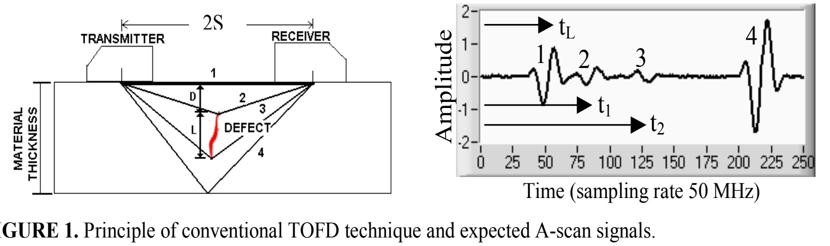

FIGURE 1. Principle of conventional TOFD technique and expected A-scan signals.

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Lateral (1) and back-wall (4) signals are used to define the region-of-interest and the two diffracted signals (2 and 3) from the two edges of an embedded crack are expected to appear in between. By knowing the transit time between the longitudinal diffracted echoes from the top (t_1) and bottom (t_2) of the crack, the defect depth and defect size may be obtained by applying the equation below [3,8]

$$d = \frac{\sqrt{v_L^2 t_1^2 - S^2}}{2} \tag{1}$$

$$L = \frac{1}{2}\left(\sqrt{v_L^2 t_2^2 - S^2}\right) - d \tag{2}$$

Where, 'D' is the defect depth, 'L' is the defect size, 'v_L' is the longitudinal wave velocity inside the material and 'S' is the distance between the probes. Here, the material is assumed to be isotropic, and the wavelength of the ultrasonic wave to be much larger than the crack tip geometry. To overcome the difficulties with inspection of thin sections and near surfaces using conventional TOFD technique, a shear wave based TOFD technique is discussed here.

BACKGROUND

Conventional TOFD technique is limited to thick sections only (thickness greater than 15 mm). Many literatures discuss the limitation of TOFD technique for inspection of thin and near surface inspections. Earlier attempts to near surface inspections have been carried out by Ido et al. [9] and Charlesworth and Hawker [10]. The near surface defects were overestimated using conventional TOFD technique [11] and to improve the accuracy requires scanning from both the surface of the specimen [12].

Our earlier attempts in using TOFD technique for plates less than 10 mm thick were done by using miniature probes coupled with digital signal processing technique called Embedded Signal Identification Technique (ESIT) [13] and Point Source Correlation Technique [14]. This paper demonstrates the successful application of TOFD technique to thin sections and near surfaces based on shear wave diffraction technique.

INTRODUCTION TO S-TOFD

When an incident longitudinal wave front meets the defect, the wave diffracted as longitudinal diffracted wave (L) and Shear diffracted wave (S). Since the shear wave velocity is smaller (half of longitudinal wave velocity), the longitudinal diffracted wave reaches the receiver first followed by shear-diffracted wave. Figure 2 (a) shows longitudinal (L) and shear wave (S) diffraction for surface crack and the corresponding simulated signals at the receiver. The simulation for the A-scan and the B-scan in this paper used a ray tracing method [15]. When the crack tip is located at a depth not greater than 67% of the thickness of the material, the backwall reflected longitudinal wave reaches the receiver before shear-diffracted wave from the defect tip as shown in the A-scan in Figure 2 (b). Additionally, the mode converted L-S wave from the backwall is also shown.

From the figure it is observed that even the longitudinal diffracted echo from the defect tip superimpose with the lateral wave (defects in thin and near surface), the shear diffracted echo from the defect is clearly separated. The defect depth and size can be measured from the shear diffracted signals using the given equations [16]

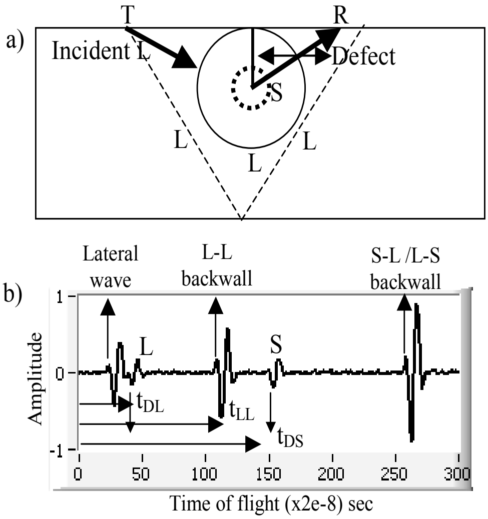

FIGURE 2. Longitudinal and shear wave diffraction for a surface cracks. L and S are the longitudinal and shear wave-diffracted echo from the defect tip. a) the defect configuration and b) signal at the receiver.

$$D = \sqrt{\frac{v_L^2 t_{st}^2}{(n+1)^2} - S^2} \tag{3}$$

$$L = \sqrt{\frac{v_L^2 t_{sb}^2}{(n+1)^2} - S^2} - D \tag{4}$$

Where, the depth of the defect is 'D' and length is 'L' $n = v_L / v_S$. For the longitudinal incidence and longitudinal diffraction, $n = 1$, then equations 3 and 4 reduces to equations 1 and 2. The required minimum probe separation (X) for which the shear diffracted echo appear after longitudinal reflected echo is given by equation 5. [16]. The effect is shown in Figure 3.

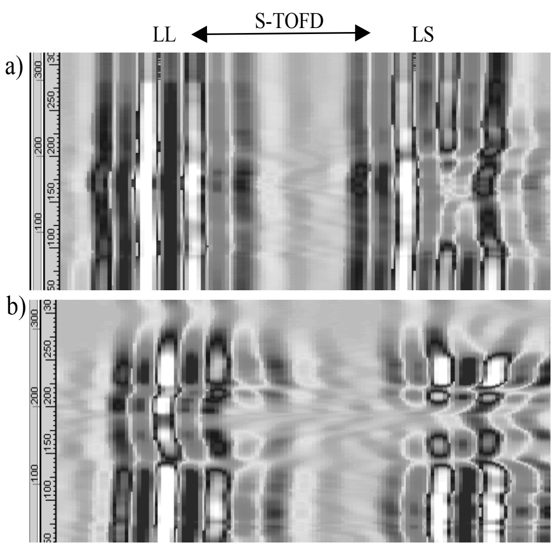

FIGURE 3. The difference between a) optimal and b) suboptimal transducer positions for 3 mm surface defect in 10 mm thick aluminium sample.

$$X > 2\sqrt{\frac{H^2 - RL^2}{R-1}} \tag{5}$$

Where,

$$R = \frac{1}{4}\left(1 + \frac{v_L}{v_S}\right)^2$$

'L' is the crack length from the scanning surface in a specimen of thickness 'H'. The distance between transmitter (T) and receiver (R) is 'X'.

Equation 5 is the minimum probe separation required for shear diffracted echo appear after longitudinal reflected echo. When depth of the defect tip that is diffracting (L) is greater than 67% of the thickness (H), the equation 5 becomes ill conditioned i.e. the diffracting crack tip should lie within 67 % of the thickness from the scanning surface to get the arrival time shear tip diffracted signal greater than the arrival time of the longitudinal bottom reflected signal.

SIZING OF NEAR SURFACE DEFECTS

Experiments were conducted on samples with realistic fatigue cracks in thin sections. Figure 4 shows the experimental results obtained over a 2.6 mm fatigue crack in a 7 mm thick maraging steel sample. Since the spacing between lateral and backwall longitudinal reflected signals are small, the longitudinal diffracted echo is not detectable in the B-scan image. Again, the temporal spacing of shear wave region is more and the diffracted shear wave signal from the defect is clearly observed and TOF measured from the B-scan image.

SIZING OF SIMULATED PITTING CORROSION LIKE DEFECTS

Specimen was prepared to simulate pitting corrosion defects. Two EDM holes were machined from one side. The sizes of the EDM holes were approximately 0.35 mm in diameter. The sketch of the specimen is shown in Figure 5. The TOFD B-scan image obtained over the two different depths of defects is shown in Figure 6.

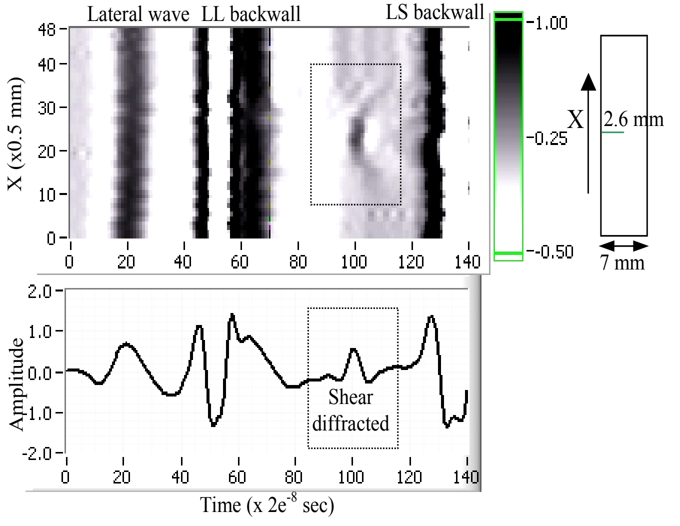

FIGURE 4. The use of shear diffracted signal to size surface open fatigue crack of 2.6 mm depth in 7 mm thick mild steel weld sample a) B-scan image and a) A-scan signal over the defect.

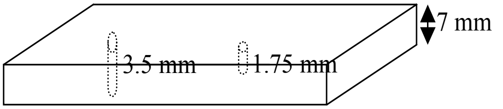

FIGURE 5. Sketch of the specimen with simulated pitting corrosion like defects.

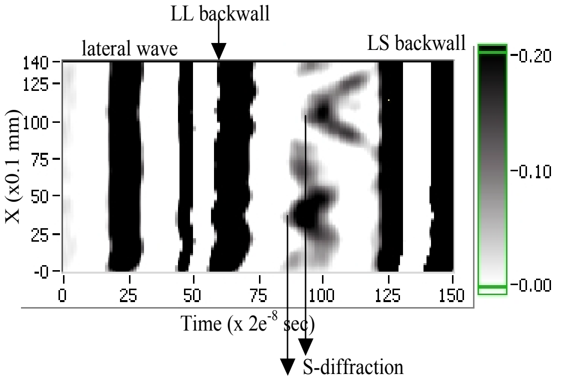

FIGURE 6. B-scan image of pitting corrosion simulated defects.

TABLE 1. Measured defect sizes using S-TOFD.

Actual depth (mm)	Specimen thickness (mm)	Measured depth using S-TOFD (mm)	% Error
4.51	7.2	4.49	0.4
2.63	6.4	2.64	0.38
3.5	7	3.48	0.57
1.75	7	1.77	1.14

From the Figure 5, it is clearly observed that the longitudinal diffracted signal from the defect is not detected but the shear diffracted signal from the defect is clearly seen and well separated. Table 1 summarizes the measured defect sizes using S-TOFD for different depth of defect in thin specimens.

SUMMARY

The S-T0FD technique, uses the advantage of the slower velocity of the diffracted shear wave for improving the time of flight measurements, and consequently improve flaw sizing. To demonstrate the near surface inspection accuracy of S-TOFD technique experiments were conducted on samples with realistic fatigue cracks and simulated EDM notches. The detection and sizing accuracy of shear diffraction based measurements is more than longitudinal diffraction based technique particularly for near surface inspection. Since the inspection material thickness is small (6-7 mm) and the material considered has less attenuation, the use of shear-diffracted wave is feasible even though diffraction coefficient of shear wave is much smaller than longitudinal wave. The ability of the developed method to image defects very near to the scanning was found to improve by 20-35% when using S-TOFD when compared to traditional TOFD using longitudinal wave.

REFERENCES

1. M.G. Silk "The use of diffraction-based time-of-flight measurements to locate and size defects", *British Journal of NDT*, **26**,208-213 (1984).
2. J.A. Ogilvy and J.A.G. Temple "Diffraction of elastic waves by cracks: application to time-of-flight inspection", *Ultrasonics*, **7**, 259-269 (1983).
3. J.P. Charlesworth and J.A.G. Temple, *Engineering Applications of Ultrasonic Time of Flight Diffraction*, Research Studies Press Ltd, England, 2001.
4. M.G. Silk "Defect sizing using ultrasonic diffraction", *British Journal of NDT,* **21**, 12-15 (1979).
5. M.G. Silk "The interpretation of TOFD data in the light of ASME XI and similar rules", *British Journal of NDT*, **31**,242-251 (1989).
6. M.G. Silk "Benefits of signal processing in ultrasonic inspection", *Insight*, **36**, 776-781 (1994).
7. Young-Fo Chang and Cheng-I Hsieh "Time of Flight Diffraction Imaging for Double-Probe Technique", *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, **49**, 776-783 (2002).
8. Mondal, "An overview TOFD method and its Mathematical Model", http://www.ndt.net/article/v05n04/mondal/mondal.htm, NDT.net, **5**, (2000)
9. Ido, N, Hatanaka, H, Arakawa, T, et al. Examination of flaw detection near the surface by the ultrasonic TOFD method, *Key Engineering materials*, **270**, 378-383 (2004).
10. J. P. Charlesworth and B.M. Hawker, "Inspection of the Near-Surface Defect Plate (DDT3) by the Ultrasonic Time-of-Flight Technique", *British Journal Of Non-Destructive Testing*, **26**,106-112 (1984).
11. J. Zippel, A. Pincheira and A. Washer, "Crack Measurement in Steel Plates Using TOFD Method" *Journal of Performance of Constructed Facilities*, **14**, 75-82 (2000).
12. F. Betti, Nuovo Pignone, G.Zappavigna, G.Pedrinzani, G.Nardoni and P.Nardoni, "Accuracy Capability of TOFD Technique in Ultrasonic Examination of Welds", 15th World Conference on Non-Destructive Testing, 2000, Rome.
13. G. Baskaran, K. Balasubramaniam, C.V. Krishnamurthy and C. Lakshmana Rao, "Ultrasonic TOFD flaw sizing and imaging in thin plates using Embedded Signal Identification Technique (ESIT)", *Insight*, **46**, 537-542 (2004).
14. G. Swamy, G. Baskaran, and K. Balasubramaniam, "A Point Source Correlation Technique For Automatic Flaw Identification And Sizing Using TOFD Inspection", **63**, 425-429 (2005).
15. G. Baskaran, K. Balasubramaniam, C.V. Krishnamurthy and C. Lakshmana Rao, "A Ray Based Model For The Ultrasonic Time of Flight Diffraction Simulation of Thin Walled Structure Inspection", *ASME Journal of Pressure Vessel Technology*, **127**, (2005).
16. G. Baskaran, K. Balasubramaniam and C. Lakshmana Rao, "Near surface inspection using shear wave time of flight diffraction technique", Communicated to NDT&E.