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Ultrasonic Time of Flight Diffraction imaging of cracks in thin sections

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Abstract

It is desired to determine the exact defect size in order to prevent catastrophic failure and/or evaluate the residual life of engineering structures, particularly in aerospace applications. Defect sizing through conventional pulse echo ultrasonic method uses the echo amplitude and DGS curves. This technique is tedious and somewhat unreliable when realistic cracks that are not normal to the wave are encountered (due to amplitude based measurement). Ultrasonic Time of Flight Diffraction (TOFD) method, based on time difference measurement between crack tip diffracted echoes is an effective method for both location and sizing the defect. This method has been shown to be successful in thick structures i.e. thickness greater than 10 mm. This paper describes efforts to extend this method to thin plates i.e. thickness less than 10 mm. An analytical model based on ray tracing was employed to design special transducers and for signal interpretation of the various mode-converted signals during TOFD investigation of thin plates. Both analytical and experimental results will be discussed.

Introduction

Time of flight (or the pulse transit time) and amplitude are the measuring parameters of most ultrasonic flaw detection techniques. Conventional ultrasonic flaw detectors use the plotting of pulse transit time and amplitude. Defect sizing using this technique is obtained by [1]

1. Comparing the signal amplitude with a reference reflector usually a standard flat bottom hole or side drilled hole specimens.
2. The amount of probe movement required for a predetermined (eg. ≈ 6 db) reduction in signal strength, in case of flaws of larger size.

For accurate flaw sizing the parameter amplitude, where the defect acts like a mirror for the ultrasound, is not enough because the amplitude of the reflected pulse may be influenced by many parameters other than the size of the reflector such as the surface roughness, transparency and orientation of the defect and the effectiveness of the ultrasonic coupling [2].

When an ultrasound meets the defect, part of energy is reflected, part of energy is transmitted, and diffraction at the edges also takes place. According to Huygen’s principle the defect tips act like a secondary sources. Hence if we were able to locate the secondary source, it would enable us to accurately estimate the defect size and depth. The method based on the diffraction of ultrasound at the edges is called Time of Flight Diffraction (TOFD) method. Diffraction causes the energy to be spread over a wider angle, so by TOFD we can detect most effectively the randomly oriented defect when compared to pulse echo technique [3].

Principle of TOFD

Silk [3] first developed the ultrasonic Time of Flight Diffraction (TOFD) technique at Harwell laboratory in the late 1970’s.

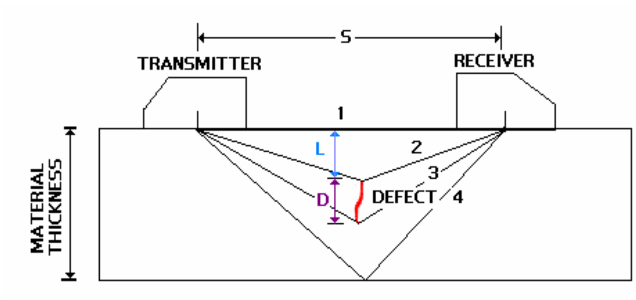

Figure 1a: The TOFD technique

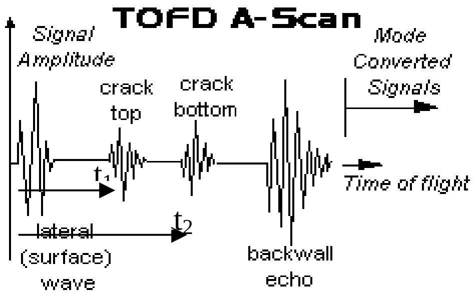

Figure 1b: Typical signals expected in TOFD

The basic principle of TOFD is shown in Figs.1a and 1b [3]. Two L-wave (Diffraction of longitudinal waves is higher than shear wave) broad beam probes of same angle preferably 55-70 degree (one is transmitter and the other is receiver) are placed on the sample in a pitch-catch like configuration as shown in Fig.1a. The distance between probes was calculated based on the thickness of the structure [3]. Four different types of waves are involved in the TOFD imaging:

1. The wave travels directly from the transmitter to the receiver called lateral wave along the surface. It has the shortest time of travel because it travels the shortest distance, and the velocity is approximately equal to the longitudinal wave velocity of the structure.

2. Diffracted wave from the top edge of the defect.

3. Diffracted wave from the bottom edge of the defect.

4. Mode converted shear wave reflection from the back wall.

Lateral and back wall echoes are used as reference and the diffracted echoes are expected to appear in between. By knowing the transit time between the diffracted echoes from the top and bottom of the crack we can calculate the defect depth and defect size by applying simple triangulation theory.

Defect size and depth determination for simple vertical defect

From Fig 1b, for a simple vertical defect the following relationships hold good [4],
The defect depth D is given by,

$$D = \tfrac{1}{2}\sqrt{c_L^2 t_1^2 - S^2} \quad \text{-- [1]}$$

The defect size L is given by,

$$L = \tfrac{1}{2}\sqrt{c_L^2 t_2^2 - S^2} - D \quad \text{-- [2]}$$

Where, t_1 is the arrival time of the signal at the receiver from the top edge of the defect
t_2 is the arrival time of the signal at the receiver from the bottom edge of the defect
S is the distance between probes
c_L is the velocity of lateral wave
Using the equations [1] and [2], the defect size and location can be computed.
For non-vertical defects, size and location can be computed from B-scan display.

Display of TOFD data

TOFD signals are usually displayed in an unrectified form because the phase of the diffracted signal contains information about the orientation of the edge from which it came.

The simplest type of data display is called A-scan display as shown in Fig.1b. The problem with this type of display is judging the significance of a small signal may be difficult. For the best detection and sizing capability, it is necessary to record A-scans as the probes are moved over the work piece. Software using LabVIEW was developed for Data Acquisition, which also controls signal parameter and motion control of the TOFD system. A two dimensional display of A-scans resulting from motion within the plane is called a B-scan, while a similar display from motion perpendicular to the plane is a D-scan.

TOFD scans with probe motion parallel to and perpendicular to the line joining them are analogous to pulse echo B and D-scans respectively, apart from the inherently non-linear depth scale in the TOFD case. In a B-scan, due to beam divergence, the tip diffracted waves will appear as arc’s and planar interface such as the back-wall will be straight lines. Measurements of defect depth and defect height are obtained by arcs and curve fitting method in B-scan display. [3]

TOFD system developed at CNDE-IITM

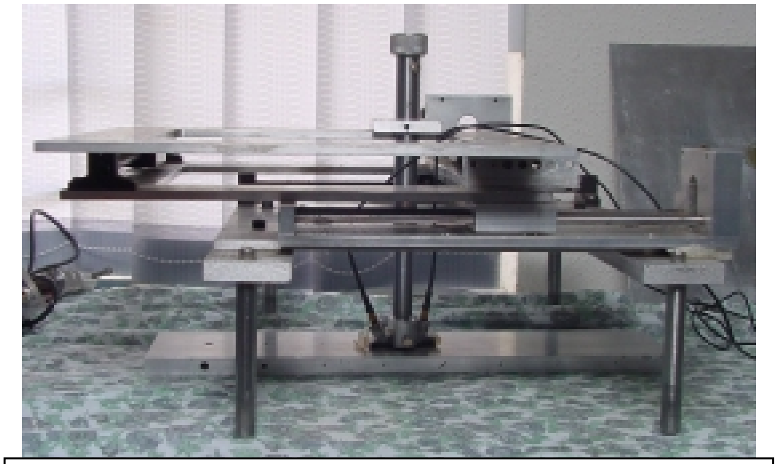

Figure 2. TOFD robotic system developed at CNDE

This TOFD system (see Fig.2) basically consists of

1. A multi-purpose X-Y scanner, which is controlled by stepper motors and integrated with the motion control hardware.
2. The spring loaded transducer holder to improve the consistency and robustness during automated scanning. The probes are connected to pulser/receiver.

Specimen Preparation

EDM notches were fabricated in weld-free Aluminum and mild steel samples of different thickness. Each calibration sample has 24 different types of defect. The details of the samples with the simulated defect are shown in Fig.3.

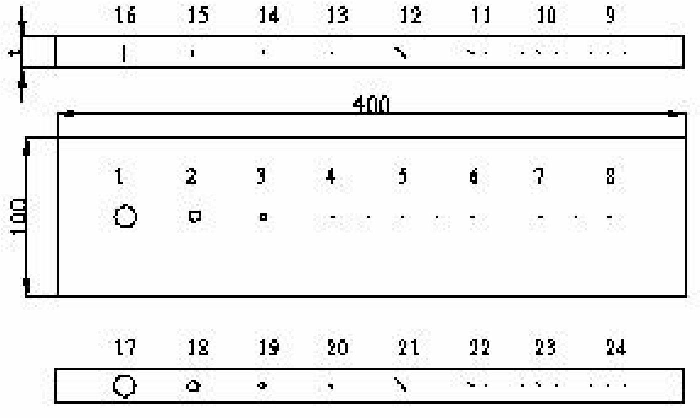

Figure 3. EDM notch details

Inspection of thin sections.

The depth of penetration and area of coverage of ultrasound inside the material depends on distance between the transmitter and receiver probes. As the thickness of the material decreases the distance between transmitter and receiver probes should also be decreased for effective testing.

The basic features involved in TOFD of thin sections are

1. The thin steel structure may lead to the un-intentional generation of mode converted wave.
2. TOFD method employing a very high frequency transducer with very short pulse. This is not feasible in thick structures due to attenuation and beam spread that will limit the sensitivity of inspection. But, for thin structure, use of high frequency ($\geq 5MHz$) may potentially be acceptable. High frequency will also improve the sensitivity to tight cracks, since the wavelength becomes very small. Also, this will allow us to detect smaller defect sizes.
3. Design of miniature probe shoes using plexiglass to obtain the required shoe distance between probes and beam divergence.
4. Develop advanced signal processing to improve defect detectability and sizing. This can involve analysis in the time-frequency domains such as wavelets and removing material noise using adaptive signal processing.
5. Using beam divergence we can cover the entire thickness of the material by a single pass over the surface and this will reduce the image quality of B-scan, but we can improve the image quality by doing Pattern Recognitions algorithms, which is explained in detail in this paper.

Experimental Results

Data was acquired from the aluminum sample of thickness 10 mm with simulated defects. Both 2.25 and 5 MHz. frequency probes were used in the data collection. Data was acquired by moving the probes over the defect and defect free region and processed by TOFD imaging software. B-scans obtained by moving the probe over the defect free and defect regions for different angles, different frequencies and different distance between transmitter and receiver are shown in the Figs.4-6.

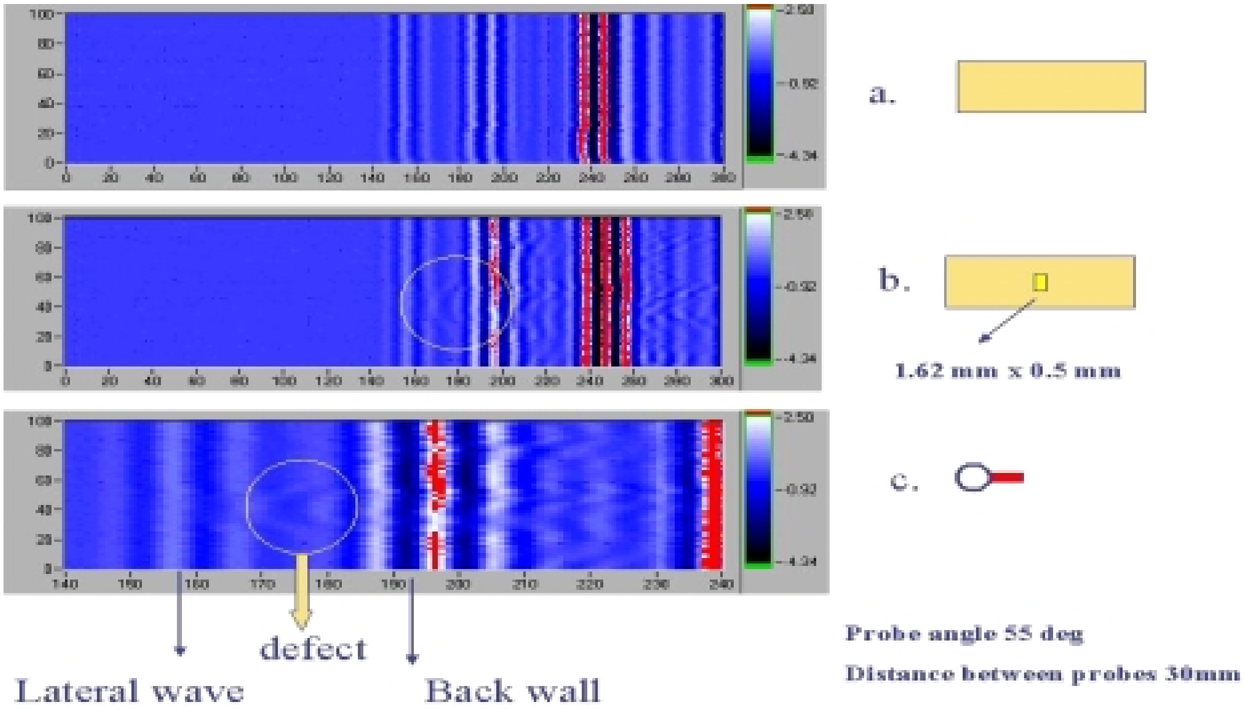

Figure 4. B-scan image of 55 deg angle, 2.25 MHz frequency and 30 mm distance between probes. (a) scan over defect free region (b) scan over a defect of length 1.62 mm and width 0.5 mm and (c) zoomed image of (b).

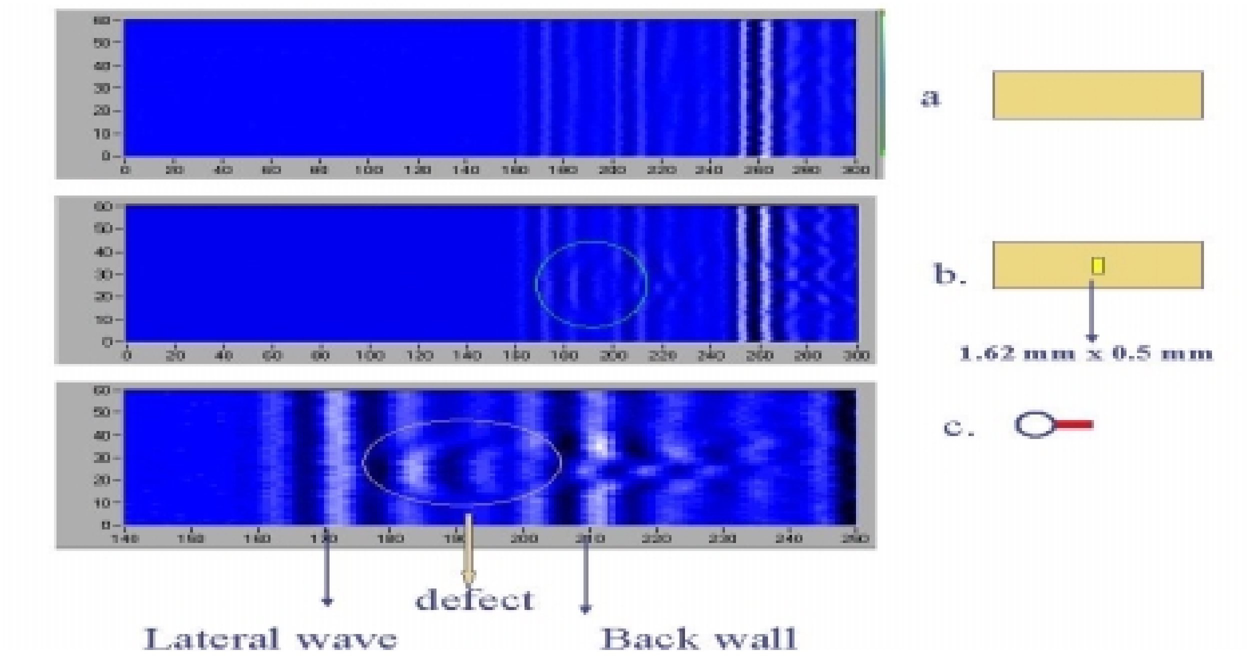

Figure 5. B-scan image of 65 deg angle, 2.25 MHz frequency and 25 mm distance between probes. (a) scan over defect free region (b) scan over a defect of length 1.62 mm and width 0.5 mm and (c) zoomed image of (b).

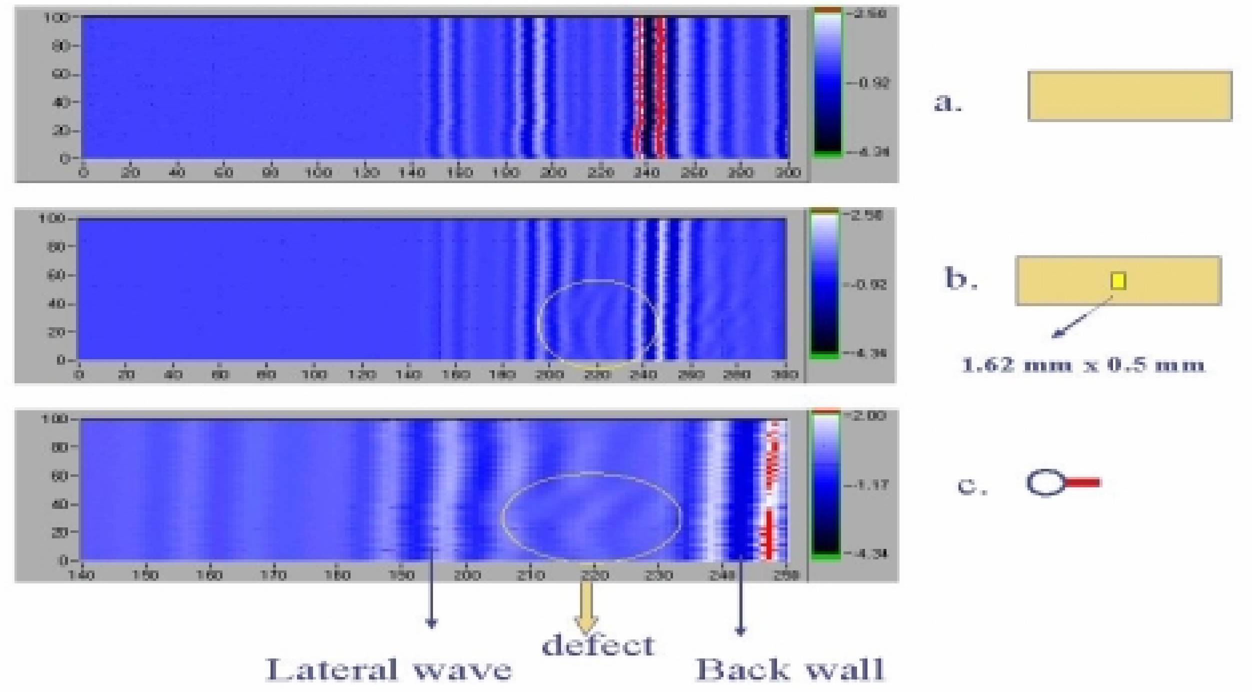

Figure 6. B-scan image of 60 deg angle, 2.25 MHz frequency and 30 mm distance between probes. (a) scan over defect free region (b) scan over a defect of length 1.62 mm and width 0.5 mm and (c) zoomed image of (b).

In the Figs.4-6, the lateral and backwall echo appear as vertical lines and we can see that defect echo (from the defect top and bottom) appearing as an arc in between the lateral wave and backwall echo.

Defect Position Analysis Using Pattern Recognition Technique

To improve the resolution and remove the mode-converted echoes, a vertical filter was used which exploited the fact that these echoes form a vertical band in the B-Scan with little intensity variation in the above direction.

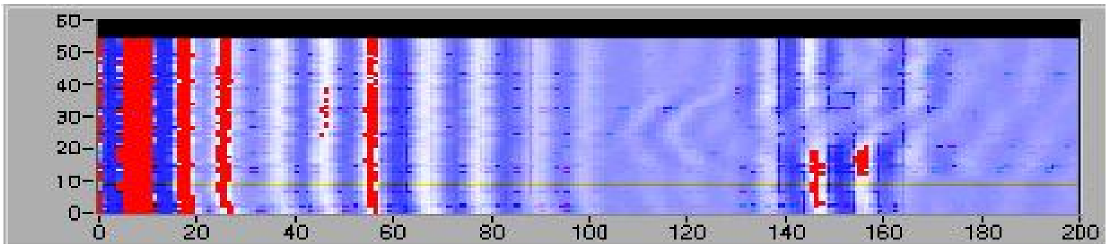

Figure 7. B-scan image obtained on a steel sample of thickness 30 mm and defect at 22 mm depth.

The resultant image (Decibel Plot), after vertical filtering and image thresholding is shown in Fig.8.

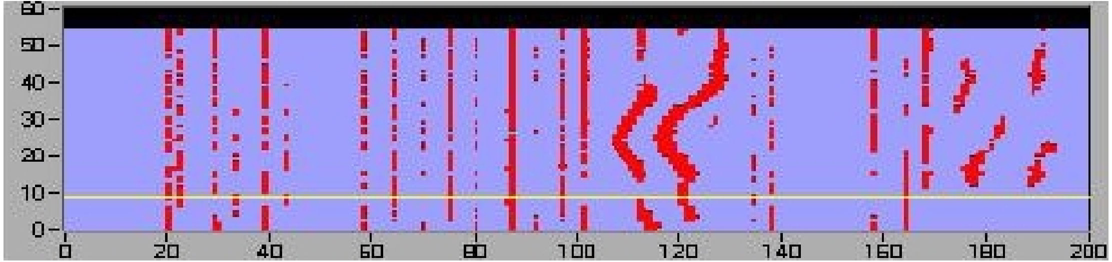

Figure 8 Decibel Plot of figure 7.

As can be seen the defect signal is clearly visible as a curved dark (red) band spanning many transducer positions. The two red bands (arcs) are defect signals from the two edges (Top and Bottom) of the same defect. A correlation filter was used to match the arc pattern. The Pattern Recognition algorithm developed for this application gives the defect position of top as well as the bottom edge using which the defect size can be characterized (for longitudinal defects) using simple Pythagoras theorem. Pattern recognition is done by comparing the theoretical model of the defect pattern to the one obtained experimentally and searching for case which gives the maximum correlation between the actual and the theoretical signal. The converged Defect position obtained, using the Pattern Recognition algorithm is shown below.

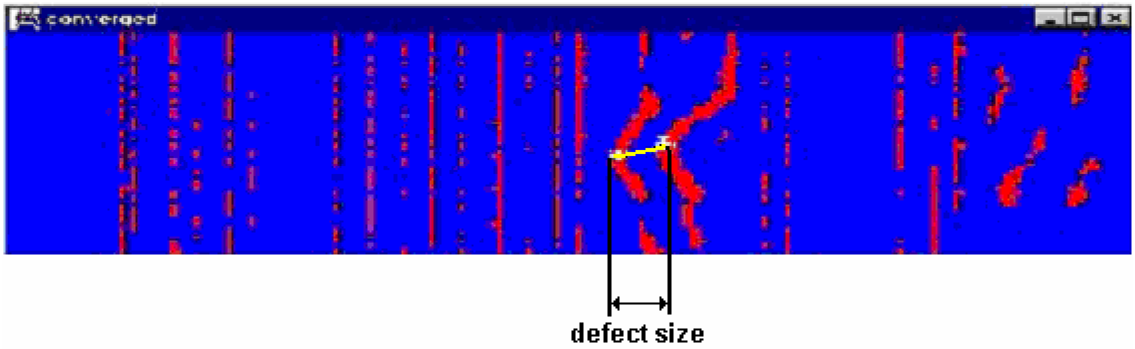

Figure 9. Processed B-scan image.

The white dots show the converged position of the defect. The yellow line is the size of the defect, which is closely matching the actual defect size. The above technique can be applied to obtain converged defect positions from Time of Flight Diffraction B-scan images. This technique may also be extended to the B-scan data using traditional pulse-echo configurations.

Summary

TOFD technique can be used for effective sizing of the defects. In our experiment we are able to size smaller defect because the size of the defect that can be detected related to beam divergence such that the defect should be completely flooded with ultrasound to cause the diffraction process. Use of higher frequency (5-15 MHz) will most likely improve the results. By using pattern recognition algorithm, we can improve the quality of B-scan image and exact location of defect signal is possible. It aids us to use broad beam ultrasound to inspect the whole thickness over a single pass.

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