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A Novel Method for Ultrasonic Evaluation of Horizontal Defects Using Time-of-Flight Diffraction

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Abstract

Time-of-flight diffraction method (ToFD) is an amplitude-independent sizing method which is based on the measurement of time-of-flight of defect tip diffracted waves. Although ToFD can measure through-wall length of defect accurately, this method is not capable of measuring horizontal defect size. In this paper, a new ToFD method for evaluating horizontal planar defects is presented. The finite element method (FEM), using the ABAQUS software package, is employed to simulate the ultrasonic wave behavior in the test blocks and its interaction with the embedded planar defects. The phased array technology is also used to model the ultrasonic inspection system parameters. FEM simulation of the new ToFD method for different crack sizes shows that, compared to the conventional ToFD method, the accuracy of results is within an acceptable range to use the novel technique for measuring the horizontal planar defects.

Keywords: Ultrasonic Wave, Diffracted Wave, Horizontal Planar Defects, ToFD

1. Introduction

Non-destructive testing has been increasingly used to assure the quality and reliability in the oil and gas pipeline industries. The ultrasonic pulse-echo technique uses the pulse flight time to locate the flaw and the echo amplitude to measure the defect size. Since the amplitude of the reflected pulses can be influenced by many parameters, such as beam spread, surface roughness, and transparency, using amplitude is not always sufficient for accurate defect sizing (Krautkramer, 1990). The basis of the time-of-flight diffraction (ToFD) technique was first initiated at the National NDT Centre, Harwell, UK. ToFD was developed mainly by Silk and his co-workers at the Harwell Laboratory over a period of about 10 years starting in the early 1970s, from a laboratory curiosity into a sophisticated full-scale inspection method capable of detecting and sizing defects in components accurately (Silk, 1973, 1974, 1976, 1978). The ToFD technique is an amplitude-independent sizing method, based on the measurement of time-of-flight of flaw tips diffracted waves. Golan and Sachese suggested a method to calculate crack size from the time delay between the arrival of a surface longitudinal reference beam and a longitudinal or shear beam diffracted from the tips of crack (Golan, 1980). Mak (Mak, 1983) developed a trigonometric method to calculate location, height, and angle of defect by a transducer located in different scan positions. The ToFD technique provides the highest possible

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accuracy in measuring the depth and through-wall length of defects (Charlesworth et al., 2001), (Baby et al., 2003), (Al-Ataby, 2012).

In 1986, the finite element simulation of ultrasonic wave propagation and its interaction with defects were conducted by Ludwig and Lord (Ludwig et al., 1986). The numerical analysis of wave propagation for ToFD in an austenitic stainless steel specimen, considering the effects of scattering at grain boundaries, was carried out by Lin et al. (Lin et al., 2006) and Connolly (Connolly, 2009). They developed an efficient method for modeling the effects of coarse grains in austenitic materials. In 2007, the simulation of the ToFD technique, using finite element method, was carried out by Baskaran et al. They used the ANSYS finite element package to model the propagation of ultrasonic waves in a thin cracked two dimensional specimen (Baskaran et al., 2006). In 2010, Honarvar and Khorasani used the ABAQUS software package to simulate the propagation of ultrasonic waves and diffraction phenomena. They compared the simulated results for drilled-hole diffraction with photo elastic snapshots (Honarvar and Khorasani et al., 2010). Although ToFD provides better accuracy in locating and sizing defects than other ultrasonic sizing methods and has a high probability of flaw detection (POD), only the through-wall length of the defect can be measured and the defect real size cannot be evaluated (Charlesworth et al., 2001). Therefore, the ToFD method cannot be used for measuring and sizing horizontal cracks (horizontal planar defects) (ASME, 2010). In this paper, a new ToFD method is presented for evaluating and measuring horizontal planar defects. The finite element method, using the ABAQUS software package, is employed to simulate the ultrasonic wave behavior in the test blocks and its interaction with the embedded planar defects. The finite element results for different crack sizes are used to study and investigate the presence and generation of different wave modes in the test block as well as the efficiency and efficacy of the new proposed method.

2. Review of the conventional ToFD method

The ToFD technique uses tip diffraction to identify the top, bottom, and ends of a discontinuity. Silk chose to use an angled compression wave for the ToFD technique rather than a shear wave, for two reasons. First, the tip diffraction signal is stronger than a shear wave diffraction signal; second, with an angled compression wave, a lateral wave is produced that can be used to measure the horizontal distance between the transmitter and the receiver.

The tip diffraction signal is generated at the tip of the discontinuity, effectively a “point” source. According to Huygens (Krautkramer et al., 1990), a point source produces a spherical wave. Figure 1-a shows a typical ToFD transducer set-up on a component with a vertical discontinuity. Figure 1-b shows both the lateral wave and a diffraction beam from the tip of a reflector. There are four sound paths from the transmitter to the receiver. Path “A” is the lateral wave path traveling just below the surface. Path “B” is the tip diffraction path from the top of the discontinuity. Path “C” is the tip diffraction path from the bottom of the discontinuity, and path “D” is the back wall echo path. Figure 2 shows a typical un-rectified received signal using ToFD. It should be noted that the phase relationships A and C are in the opposite phase to B and D. The important difference to note is between paths B and C; the top and bottom diffraction signals are in the opposite phase. This phase difference allows the practitioner to identify those points. Assuming that the diffracting tip is centered between the two transducers, the depth of crack tips below the inspection surface can be calculated by:

$$d_1 = \frac{\sqrt{(Ct_2)^2 - 4S^2}}{2} \tag{1}$$

$$d_2 = \frac{\sqrt{(C\,t_3)^2 - 4S^2}}{2} \tag{2}$$

and thereby,

$$a = d_2 - d_1 \tag{3}$$

where, a is the defect through-wall size, d_1 is the depth of the top edge from surface, d_2 is the depth of the bottom edge from surface, and $2S$ is the probe separation (Figure 1). C is the longitudinal wave velocity inside the material, t_2 and t_3 are respectively the travel times of waves diffracted from the top and the bottom of the crack (Figure 2).

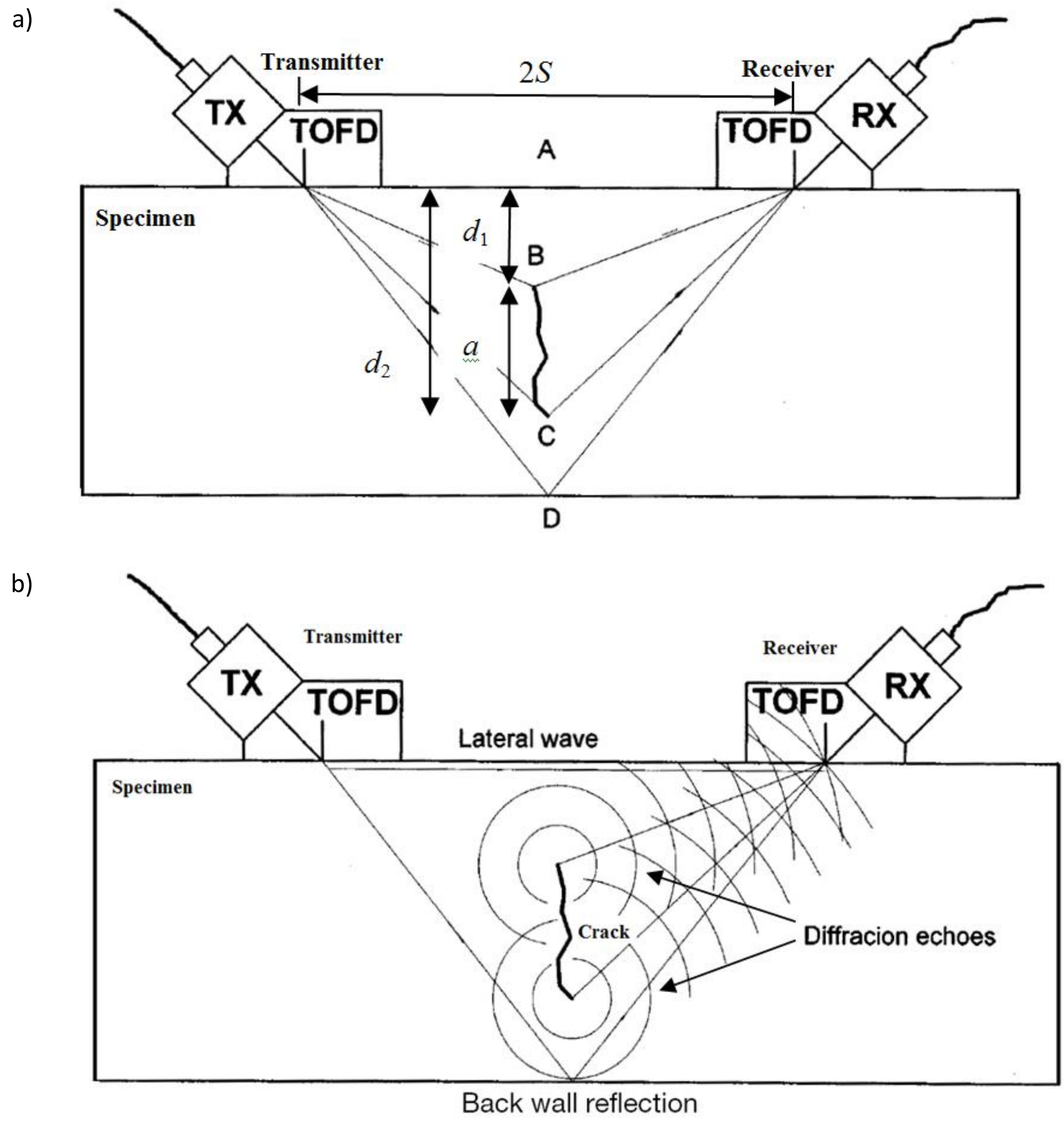

Figure 1
Configuration of time of flight diffraction technique (Hellier, 2003).

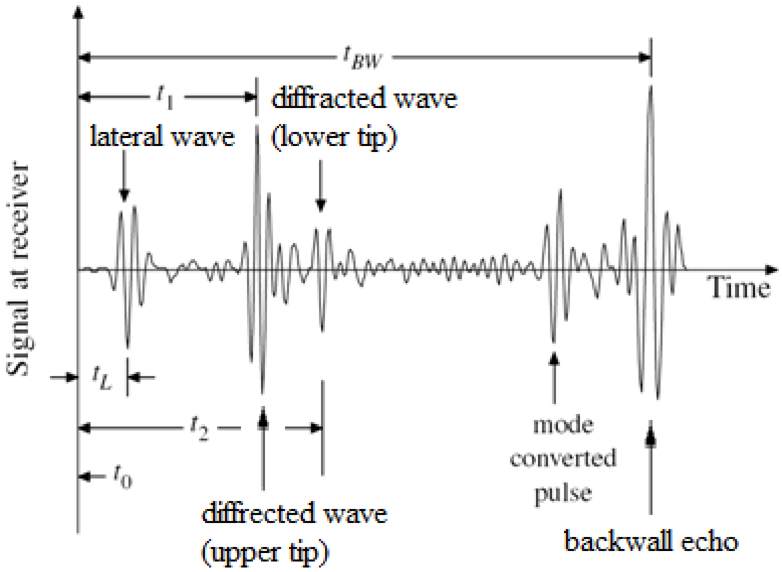

Figure 2
The time-of-flight diffraction signal (Charlesworth et al., 2001).

3. Finite element modeling of the ToFD method

In this section, the finite element method (FEM) is used to simulate the ultrasonic wave propagation in the time of flight diffraction technique. The FEM modeling consists of two basic steps: defining the mesh configuration and problem discretization, and modeling the transmitting and receiving transducers. The ABAQUS finite element software package is employed for analysis and a two-dimensional four-node quadrilateral plane strain element, CPE4R, is used in ABAQUS to discretize a carbon steel test block including vertical crack. The mesh size depends on the frequency of the propagated wave in the sample and the corresponding wavelength. The piezoelectric angle wave transducer, transmitter, is simulated by a transient single frequency pulse wave applied on the surface of the sample. The transient excitation is modeled using a cyclic single frequency pressure/force function as follows (Mardani et al., 2012):

$$p(t)=\begin{cases}(1-\cos(\frac{2\pi f t}{N}))\cos(2\pi f t), & 0<t<N/f\\ 0 & otherwise\end{cases} \tag{4}$$

where, *f* is the excitation wave frequency and *N* represents the number of cycles.

Using linear delay law for phased array transducers, the compressional excitations can be applied to the sequential elements so that ultrasonic wave propagates at a specific angle, θ_S. The delay time between adjacent elements, or nodes, is calculated using Hyphen's principle (Olympus NDT, 2007):

$$\Delta t=\frac{d\sin\theta_s}{C} \tag{5}$$

where, *d* is the distance between two adjacent elements, θ_s stands for the steering angle of propagation, *C* is the longitudinal wave speed in the media, and Δ_t is the time delay between two adjacent elements.

To investigate the convergence of the results and the appropriate element size for a 2 MHz frequency ultrasonic wave, the signal-to-noise ratio (SNR) is obtained for different element sizes. As it can be seen in Figure 3, at $f = 2$ MHz, the maximum SNR and SNR convergence occurs for the element sizes smaller than 60 μm.

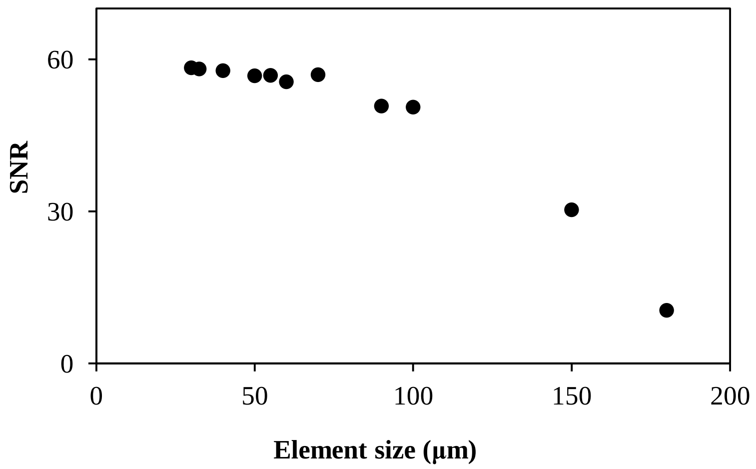

Figure 3
The effect of element size on SNR convergence.

4. The proposed method

As it was mentioned before, using the conventional ToFD method in Equations 1 to 3, the difference between time-of-flight diffractions of upper and lower crack tips gives the defect through-wall size, whereas the actual defect size cannot be measured. This means that the conventional ToFD technique leads to large errors for oblique defects and cannot be used for horizontal defects. In the proposed method, a novel configuration and the corresponding formula are used so that the ToFD method can be employed to evaluate horizontal planar defects. Figure 4 shows the proposed ToFD configuration on the specimen with a horizontal planar discontinuity. As it can be seen, in this configuration, two transducers including a transmitter/receiver, No. 1, and a receiver, No. 2, are located at the both sides of the defect.

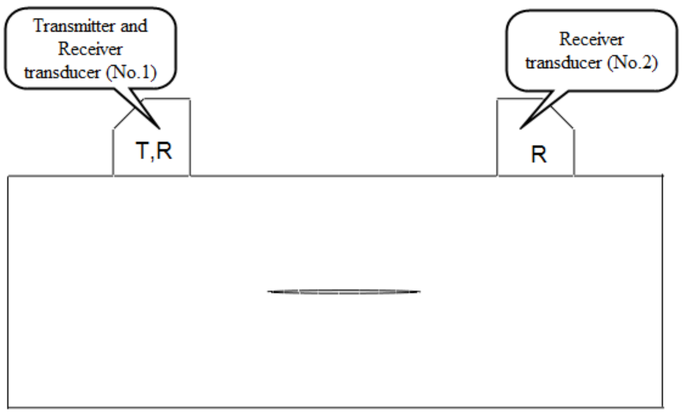

Figure 4
The proposed ToFD configuration for horizontal planar defects.

The ultrasonic wave propagation, in this configuration, is simulated using the ABAQUS software to study the behavior of ultrasonic wave modes in the test block and their interaction with the defect. In Figure 5, the different incident ultrasonic wave modes are shown. The transmitting transducer, T_1, emits a short pulse of ultrasonic wave, longitudinal wave, into the component and energy spreads out as it propagates into the specimen. If the crack face is smooth, there will be a mirror-like reflection of the wave incident on the face (see Figure 6). For any horizontal planar discontinuity, whether smooth or rough-faced, diffraction from the edges of the defect causes some fraction of the incident energy travel towards the receiving transducers R_1 and R_2 in longitudinal and shear modes at different wave velocities. As it can be seen in Figures 6 and 7, the mode conversion behavior due to the interaction of ultrasonic wave with the defect leads to the presence of longitudinal and shear waves from each tip of the defect. Moreover, three different wave modes, including longitudinal lateral, shear lateral, and Rayleigh waves travel from the transmitting transducer, T_1, to the receiving transducer, R_2. (Figure (5)).

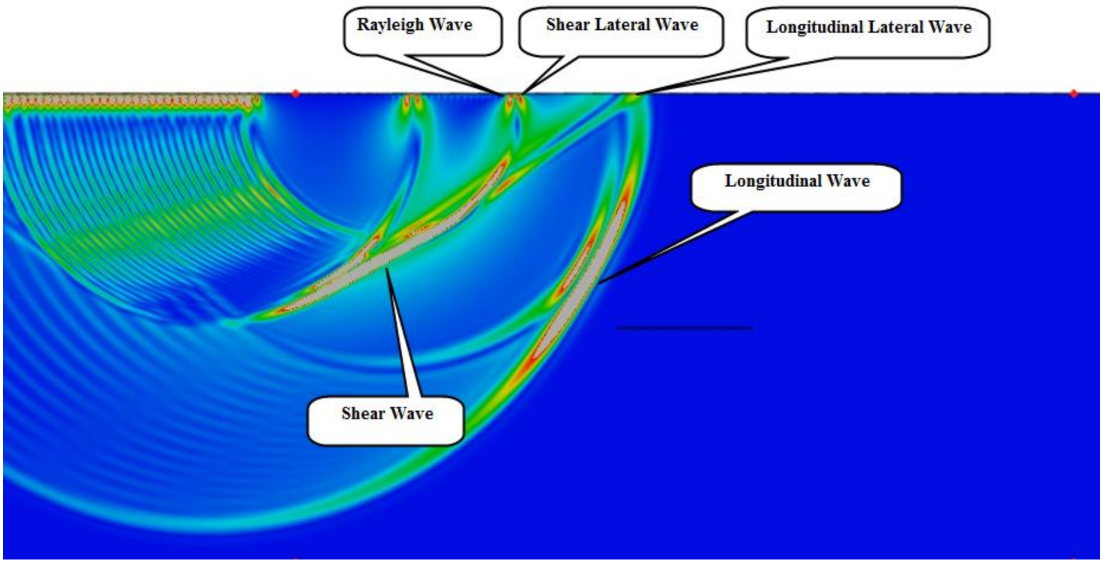

Figure 5
Ultrasonic wave excited modes in ToFD method (before striking defect).

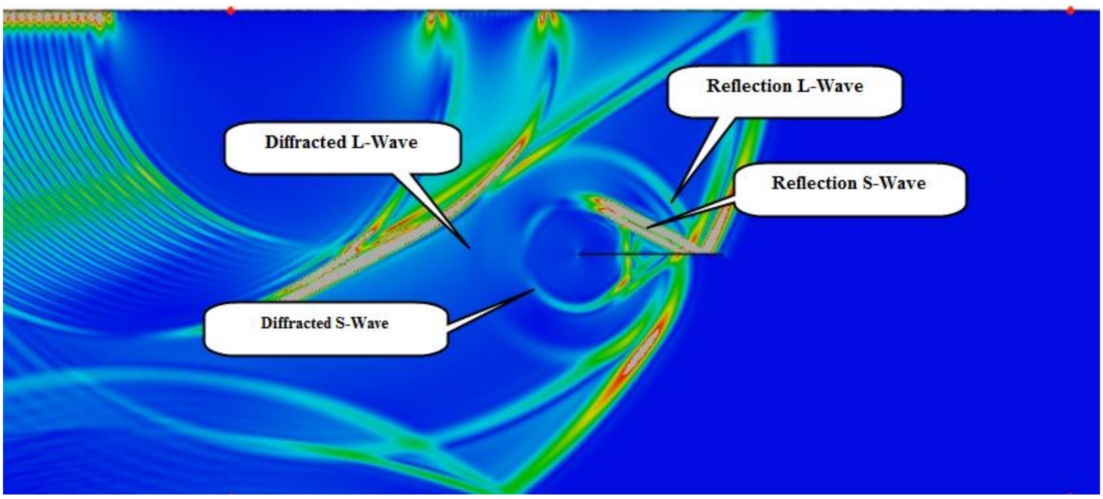

Figure 6
Ultrasonic wave modes during striking defect.

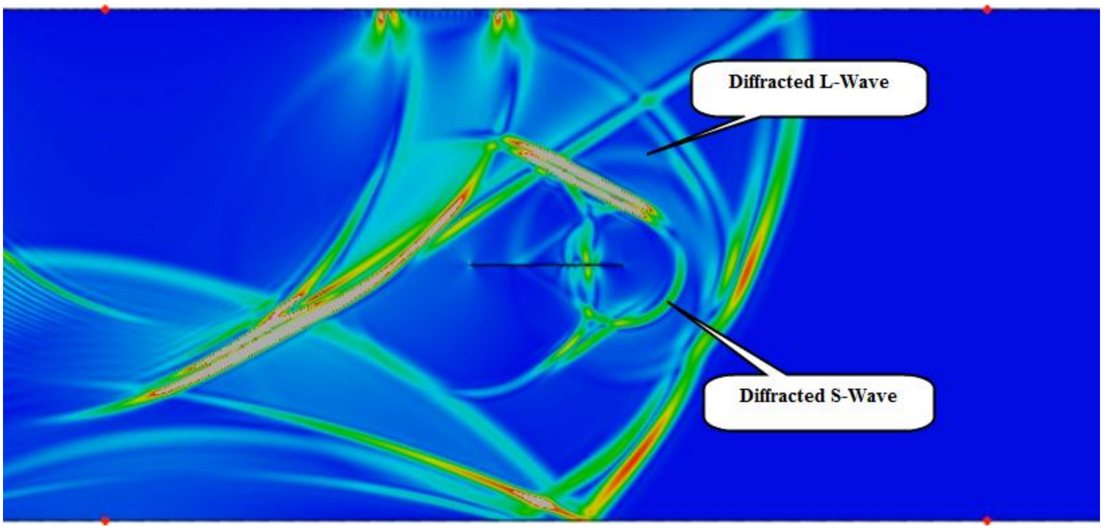

Figure 7
Ultrasonic wave propagating modes after striking defect.

If the crack is large enough, the signals from the two ends of the defect will be sufficiently separated in time to be recognized as coming from separate sources. Therefore, using this configuration and the related ultrasonic wave propagation simulation, the time difference between the received longitudinal diffracted waves from the left and right defect tips to each receiver, R_1 and R_2, can be employed to measure the horizontal defect size. It should be noted that the new method can also be used for evaluating the vertical defects. The calculation of the horizontal defect size using Pythagoras' theorem reads:

$$l = \frac{(L_2 - (L_1/2))^2 - (L_1/2)^2}{2S} \tag{6}$$

and

$$L_1 = t_1 C_L , \qquad L_2 = t_2 C_L \tag{7}$$

where, t_1 is the arrival time of the signal diffracted from the left tip of the defect by receiver 1, R_1, and t_2 is the arrival time of the signal diffracted from the right tip of the defect by receiver 2, R_2. C_L is the longitudinal wave velocity and 2*S* represents the separation between the transducers.

5. Results and discussions

To investigate the efficiency and efficacy of the proposed method, using finite element modeling, the novel method is applied to eight carbon steel blocks with different size embedded horizontal cracks. The test blocks have 100 mm lengths and 20×20 mm^2 cross sections and are modeled with the ABAQUS finite element software package using CPE4R plane strain elements. The acoustic and elastic properties of carbon steel are given in Table 1. Each block contains a horizontal planar defect. The defects have lengths of 2, 4, 6, 8, 10, 12, 14, and 16 mm and a depth of 12 mm depth, as can be seen in Figure 4. The transmitter is modeled as an 8-element 2 MHz phased array transducer. Each element of the phased array transducer has 0.5 mm length and the gap space between two adjacent elements is 0.1 mm. The first receiving transducer is located on the position of the transmitter and the second is located at 35 mm distance from the transmitter on the inspection surface, 2S = 35 mm. The ABAQUS finite element software package is used to simulate the new ultrasonic ToFD method. The received signals at the first and the second receivers are shown in Figures 8 and 9. In Figure 8, the first echoes are related to the transient pulse waves given by Equation 4. These echoes are generated by the eight elements of the phased array transducer with a specific delay time, Equation 5, and are received by the first receiver. In this signal, the second echo is related to wave diffraction from the left tip of the defect, which is detected by the first receiver, R_1. The back-wall reflection from back surface of the block is shown as the third echo in this Figure. Figure 9 shows the signal received by the second transducer, R_2. In this signal, the first echo is due to the longitudinal mode of the lateral wave, which travels from transmitter to the receiver 2, R_2, and the second echo is diffracted wave from the right tip of the horizontal defect. Figures 5, 6, and 7 show the corresponding waves propagated in the test block. Using the signals detected by the receiving transducers, the corresponding times due to diffracted echoes from the defect tips (left and right) are determined, and then the horizontal defect size is measured using Equations 6 and 7.

Table 1
The acoustic and elastic properties of carbon steel.

ρ (g/cm^3)	E (GPa)	ν	CL (m/s)	CS (m/s)
7.85	207	0.3	5985	3210

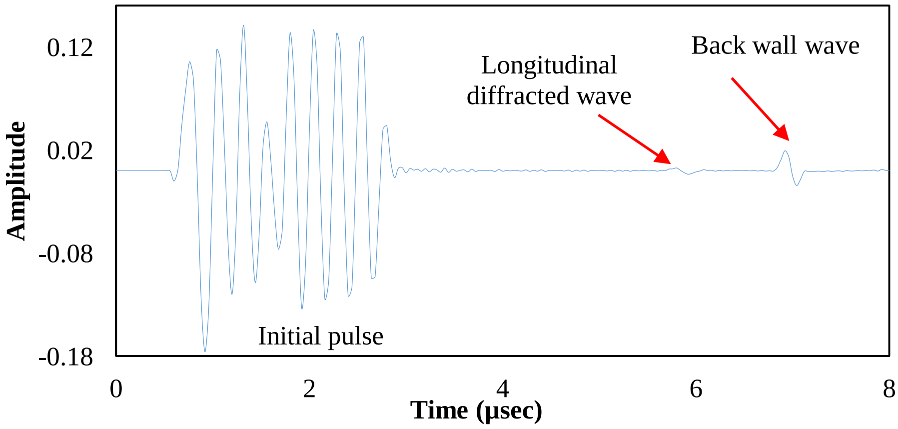

Figure 8
Time-of-flight diffraction signal detected by receiver 1, R_1.

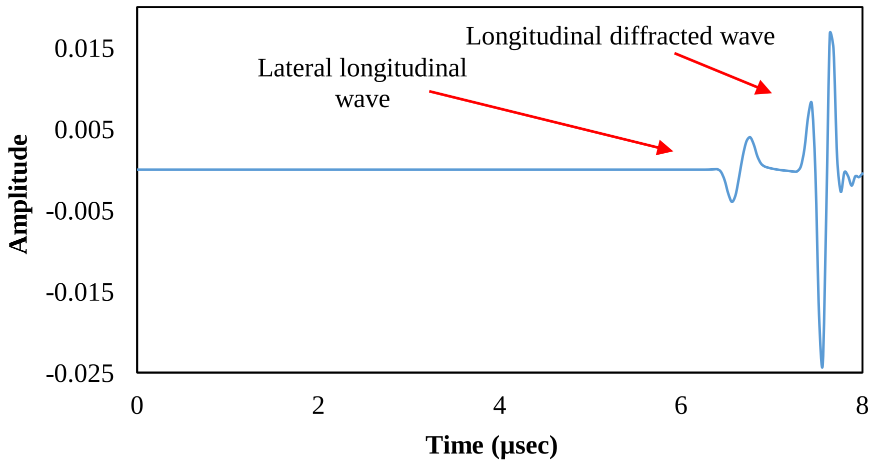

Figure 9
Time-of-flight diffraction signal detected by receiver 2, R_2.

The new method is carried out on eight carbon steel blocks with different size embedded horizontal cracks. The measured crack size resulting from the FEM simulation of each block is shown in Table 2. The comparison of the simulated and the measured crack size results shows that the maximum error which occurs at 2 mm crack size is 19.7%. As it can be seen in Table 2, the measured crack size error is minimized within the crack size range of 8-14 mm, and it slightly increases for larger defects. This agrees with the conventional ToFD results, which show higher measurement errors at smaller crack sizes (Charlesworth et al., 2001). The review of the simulated results of different crack sizes shown in Table 2 indicates that the accuracy of the proposed method for horizontal cracks, comparing to the conventional method for vertical cracks, is within an acceptable range.

Table 2

Comparison of the measured defect size with the actual defect size.

Actual crack size (mm)	t_1 (μs)	t_2 (μs)	Measured crack size (mm)	Relative error %	Incident angle (degree)
2	3.3759	3.6409	2.39	19.73	50
4	3.1529	3.6409	4.41	10.25	50
6	4.0003	4.8450	6.57	9.50	60
8	3.7532	4.8506	8.54	6.75	60
10	3.5196	4.8556	10.41	4.18	60
12	3.3138	4.8657	12.12	1.07	60
14	3.1315	4.8655	13.55	3.21	60
16	2.9418	4.8602	14.97	6.40	60

6. Conclusions

In this paper, a new time of flight diffraction (ToFD) method to evaluate horizontal planar defects was presented. The finite element method was employed to simulate the ultrasonic wave behavior in the test blocks and its interaction with the embedded planar defects such as cracks. The phased array technology was also used to model the ultrasonic inspection system parameters. The simulation of the new ToFD method for different crack sizes, using the ABAQUS finite element package, showed that, compared to the conventional ToFD method, the result accuracies are within an acceptable range to use the novel technique for measuring the horizontal planar defects. The application of the new method for eight carbon steel blocks with different size horizontal cracks (2–16 mm) indicated that the maximum error occurs at a 2 mm crack length. Finally, it was observed that the measured crack size error was minimized within the range of 8-14 mm, and that it slightly increased for larger defects.

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