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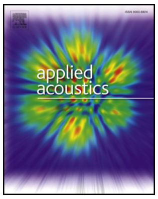

Modified ultrasonic time-of-flight diffraction testing with Barker code excitation for sizing inclined crack

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ABSTRACT

Effectively sizing inclined cracks inside material is a difficult issue in ultrasonic non-destructive testing. To size the length, depth and orientation of inclined crack, a modified ultrasonic time-of-flight diffraction testing with double receivers (DR-TOFD) using Barker code excitation is proposed. The DR-TOFD technique is excited by Barker code, which has accurate time precision, and the diffraction wave of the crack tips is received by two receivers. The diffraction signals are compressed by matched filter to obtain desired detecting signals, which are used to estimate the length, depth and orientation of crack. Finite element method, which simulates wave propagation in specimen with a 6 mm crack with different inclination angles, is used to evaluate the detecting ability of the DR-TOFD with Barker code excitation. The simulation results show that the time precision of the proposed technique is up to 0.01 μs. Experiment is also performed to verify the detecting ability of DR-TOFD. The experiment results show that the proposed technique is able to expediently and accurately size inclined crack.

1. Introduction

Ultrasonic non-destructive testing (NDT) is one of the most effective methods to test and evaluate the material, and it is widely used in industry for lower cost, convenient operation and better precision compared to other non-destructive testing methods [1]. Except for detecting, ultrasonic non-destructive testing is able to size both surface flaws, e.g. cracks, and internal flaws, e.g. cracks. Nowadays, ultrasonic non-destructive testing techniques are mainly based on: (1) amplitude of the echo or spectral of the received signal [2,3], (2) time-of-flight (TOF), such as AATT (Absolute Arrival Time Technique), RATT [1,4] (Relative Arrival Time Technique) and TOFD [5–7] (Time of Flight Diffraction). The TOF-based techniques are now more extensively applied due to their excellent probability of detection and accurate measurement of flaws. Kolkoori [8] presented an analytical approach for simulation of ultrasonic diffracted wave signals from cracks in two-dimensional geometries based on a novel HFDM (Huygens-Fresnel Diffraction Model). Cong S [9] has combined ultrasonic TOFD with LFM (Linear Frequency Modulation) to improve the SNR (Signal to Noise Ratio) and time precision. However, these conventional TOF-based techniques, such as [8,9], hold the supposition that cracks are perpendicular to the surface, which does not hold in general and causes error while testing [10]. Therefore, it's necessary to overcome the deficient supposition and to effectively evaluate inclined crack, but few methods could be used to size inclined crack well. Recently, Hoseini [1] proposed a modified relative time technique for the length and the orientation of inclined cracks using ultrasonic B-scan signals. However, the modified RATT demands B-scan, which is complex and restricted to back surface-cracks only. To effectively quantify the orientation of inclined cracks inside material expediently, the method of double receivers based on TOFD (DR-TOFD) is proposed in this paper. The difference of travelling time and path between the ultrasonic signals received by the two receivers is utilized to acquire the position of crack tips, and further the length, depth and orientation of inclined crack could be obtained. However, the DR-TOFD demands precise time precision due to the square of longitudinal wave velocity illustrated in Eq. (5). Therefore, the Barker code [11], which has desired time precision, is introduced to combine with DR-TOFD.

Coded excitation, used to solve the contradiction between detecting depth and detecting precision [12–14], was used in radar system at the earliest [15], which has been gradually introduced into ultrasonic non-destructive detection [9,11,16–18]. Chirp, Golay, and Barker are three types of codes widely used in ultrasonic non-destructive testing, and compared to the other two codes, Barker code excitation, which uses binary sequences, has an advantage in hardware implementation. Moreover, the Barker code has the least side-lobe level in the auto-correlation function among all binary sequences of the same length [19].

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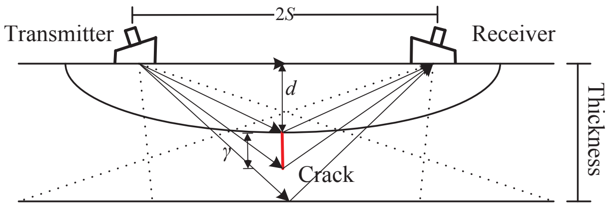

Fig. 1. Principle of the conventional ultrasonic TOFD technique.

2. Modified ultrasonic DR-TOFD

2.1. The conventional ultrasonic TOFD

With the excitation of longitudinal wave inside material, the lateral wave runs along the surface; the back wall echo reflects the bottom surface of the test object and reach to the receiver; the other two signals, upper crack tip diffracted signal, and lower crack tip diffracted signal appear due to inhomogeneity [20]. By knowing the transmitting time between the longitudinal-diffracted echoes form the top and bottom of the crack, the defect depth and the defect size could be obtained by applying the expressions below [21]. The principle of conventional ultrasonic TOFD is illustrated in Fig. 1, where the largest radiation region of each transducer is represented as the dotted line.

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

$$\gamma = \frac{1}{2}(\sqrt{C^2t_2^2 - S^2}) - d \tag{2}$$

where d is the defect depth; γ is the defect size; C is the longitudinal velocity inside the material; and $2S$ is the distance between the probes.

According to the ellipse definition, the excited and received transducer position are the two focuses of the ellipse, for the sum of the distances between the track point and two fixed points is a constant, and this track is ellipse. The traveling times of diffraction points on the ellipse are same within the overlap of the radiation of two probes. If the diffraction point (crack tip) is not on the perpendicular bisector of the two probes, the detecting value of the depth is not accurate. Furthermore, the parallel scan could provide commendable precision, however the specimen such as weld may hinder the shift of probes to introduce detection dead zone. The conventional ultrasonic TOFD technique is able to size vertical cracks precisely, which, however, is not able to precisely quantify the orientation of inclined cracks.

2.2. The principle of ultrasonic DR-TOFD

Illustrated in Fig. 2, in DR-TOFD, the crack is positioned between the transmitter and the two receivers asymmetrically, where the dashed lines represent the ellipse track. In the figure, $E(x_E, 0)$ is the transmitting probe; $R1(x_1, 0)$, $R2(x_2, 0)$ are the two receiving probes respectively; $F(x_F, y_F)$ is the diffraction point (the upper crack tip or the lower crack tip).

According to the relationship between the traveling time of diffracted wave, ultrasonic velocity and traveling journey, two independent equations are given by:

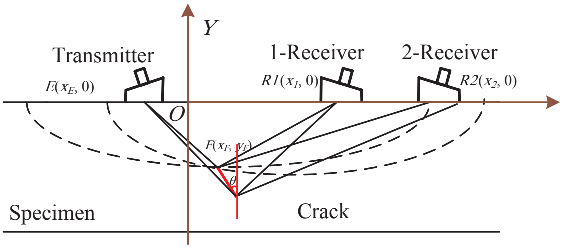

Fig. 2. Principle of the ultrasonic DR-TOFD technique.

$$\sqrt{(x_E - x_F)^2 + y_F^2} + \sqrt{(x_1 - x_F)^2 + y_F^2} = Ct_1 \tag{3}$$

$$\sqrt{(x_E - x_F)^2 + y_F^2} + \sqrt{(x_2 - x_F)^2 + y_F^2} = Ct_2 \tag{4}$$

where t_1, t_2 are the times of diffracted wave received by $R1$、$R2$; C is the longitudinal velocity inside the material.

Rearranging the above equations, a quadratic equation with one real root is given by:

$$\left[\frac{v^2}{(Ct_2)^2} - \frac{q^2}{(Ct_1)^2}\right]x_F^2 + \left[\frac{wv}{(Ct_2)^2} - \frac{pq}{(Ct_1)^2} + 2x_2 - 2x_1\right]x_F + \left[\frac{w^2}{(Ct_2)^2} - \frac{p^2}{(Ct_1)^2} + x_1^2 - x_2^2\right] = 0 \tag{5}$$

where,

$$\begin{cases} p = (x_E^2 - x_1^2 - C^2t_1^2) \\ q = (x_1 - x_E) \\ w = (x_E^2 - x_2^2 - C^2t_2^2) \\ v = x_2 - x_E \end{cases} \tag{6}$$

In Eq. (5), only the real root is the abscissa position of the diffraction point, and correspondingly the ordinate position could be obtained. The position of the diffraction point is given by:

$$\begin{cases} x_F = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \\ y_F = -\sqrt{\frac{w^2 + 4v^2x^2 + 4wvx}{4C^2(t_2 - t_1)^2} - (x_1 - x_F)^2} \end{cases} \tag{7}$$

where,

$$\begin{cases} a = \frac{v^2}{(Ct_2)^2} - \frac{q^2}{(Ct_1)^2} \\ b = \frac{wv}{(Ct_2)^2} - \frac{pq}{(Ct_1)^2} + 2x_2 - 2x_1 \\ c = \frac{w^2}{(Ct_2)^2} - \frac{p^2}{(Ct_1)^2} + x_1^2 - x_2^2 \end{cases} \tag{8}$$

By knowing the detecting parameters (transmitting probe position, receiving probe positions, the longitudinal wave velocity and the times of diffracted wave received by 1-Receiver and 2-Receiver), the position of the diffraction point could be obtained rapidly and exactly. Considering the positions of upper crack tip and bottom crack tip are X_u (x_u, y_u), X_b (x_b, y_b), respectively, the depth d, orientation θ and length γ of the crack could be given by:

$$\begin{cases} d = y_u \\ \theta = \arctan\left(\frac{y_u - y_b}{x_u - x_b}\right) \\ \gamma = \sqrt{(x_u - x_b)^2 + (y_u - y_b)^2} \end{cases} \tag{9}$$

2.3. DR-TOFD combined with Barker code

The Barker code excitation, which uses binary sequences, is one of the common code excitation methods for its least side-lobe level in the autocorrelation function among all binary sequences of the same length. Based on this technology, the ultrasonic signal can be changed from large time width, low amplitude to small time width, high amplitude.

r(t) is assumed as the reference signal constituted by a series of coherent narrower pulses, which is the excitation signal. The reference signal $r(t)$ can be expressed as:

$$r(t) = \begin{cases} \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} B_k m(t - kT), & 0 < t < NT \\ 0, & \text{others} \end{cases} \tag{10}$$