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Quantitative simulation of ultrasonic time of flight diffraction technique in 2D geometries using Huygens–Fresnel diffraction model: Theory and experimental comparison

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ABSTRACT

This article presents an analytical approach for simulation of ultrasonic diffracted wave signals from cracks in two-dimensional geometries based on a novel Huygens–Fresnel Diffraction Model (HFDM). The model employs the frequency domain far-field displacement expressions derived by Miller and Pursey in 2D for a line source located on the free surface boundary of a semi-infinite elastic medium. At each frequency in the bandwidth of a pulsed excitation, the complex diffracted field is obtained by summation of displacements due to the unblocked virtual sources located in the section containing a vertical crack. The time-domain diffracted wave signal amplitudes in a general isotropic solid are obtained by standard Fast Fourier Transform (FFT) procedures. The wedge based finite aperture transducer refracted beam profiles were modelled by treating the finite dimension transducer as an array of line sources. The proposed model is able to evaluate back-wall signal amplitude and lateral wave signal amplitude, quantitatively. The model predicted range-dependent diffracted amplitudes from the edge of a bottom surface-breaking crack in the isotropic steel specimen were compared with Geometrical Theory of Diffraction (GTD) results. The good agreement confirms the validity of the HFDM method. The simulated ultrasonic time-of-flight diffraction (TOFD) A-scan signals for surface-breaking crack lengths 2 mm and 4 mm in a 10 mm thick aluminium specimen were compared quantitatively with the experimental results. Finally, important applications of HFDM method to the ultrasonic quantitative non-destructive evaluation are discussed.

1. Introduction

The ultrasonic wave diffraction from the tip of the cracks has been widely used for sizing of the defects particularly in pressure vessel components of a water reactor [2–4]. The ultrasonic time-of-flight diffraction (TOFD) technique is a well established non-destructive testing and evaluation (NDT&E) method for the accurate sizing of embedded as well as surface-breaking cracks [5–9]. Mathematical models for ultrasonic non-destructive inspection have proved to be an important component in the design and validation of inspection procedures [10]. System models which include all aspects of the inspection process, from the behaviour of the probe to scattering of the flaw, are particularly useful for optimal selection of experimental parameters and the interpretation of experimental data [11,12]. Quantitative evaluation of relative strengths of the diffracted signals is very important for the ultrasonic non-destructive evaluation (NDE) of safety relevant engineering materials in order to ensure the detectability of the defect.

Edge diffraction phenomena from the cracks whose characteristic dimensions are greater than the ultrasonic wavelength has been described based on the Geometrical Theory of Diffraction (GTD) by Ogilvy and Temple [13] and Coffey and Chapman [14]. In the high-frequency domain, the diffraction of elastic wave by cracks based on the elastodynamic ray theory was presented by Achenbach et al. [15,16]. Darmon et al. [17–19] presented the semi-analytical scattering models for the simulation of ultrasonic NDT. They used the Kirchhoff approximation to model the specular reflections from defects and GTD to obtain scattering amplitudes from crack edges. GTD fails at predicting accurate amplitudes for diffracted signals when the direction of observation close to (a) the direction of specular reflection, (b) the shadow boundary and (c) the critical

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longitudinal angle for shear waves [19]. To use GTD efficiently, singularities at shadow boundaries need to be handled with care although these singularities do not seem to occur for typical TOFD configurations encountered in the field. A two-dimensional ray-based model using GTD theory to simulate the TOFD A-scan signals and B-scan images in isotropic plate like structures was presented by Baskaran et al. [20].

Her and Lu [21] presented experimental investigations on diffraction of elastic waves on the tip of the artificial slots in steel (Fe), aluminium (Al) and brass materials and compared the experimental diffracted amplitudes with the GTD based theoretical predictions. GTD was employed to calculate the diffracted wave amplitudes from defects in plates for the incidence from a normal point force and a thermo-elastic source [22]. Chapman [23] presented a system model based on the both GTD and Kirchhoff theories for simulating ultrasound scattering from planar cracks in isotropic materials. An efficient probabilistic acoustic-diffraction model based on the Huygens–Fresnel principle for sonel mapping in environmental acoustics was presented by Kapralos et al. [24].

In the present work, a modelling approach is proposed for the quantitative simulation of ultrasonic diffracted wave signal amplitudes based on the Huygens–Fresnel concepts originally enunciated for optical phenomena [25]. In contrast to GTD, the proposed model is free from singularities. Additionally, the model is capable of evaluating the lateral wave, back-wall reflected wave and the mode-converted wave signal amplitudes which generally occur in the ultrasonic TOFD inspection of engineering materials.

The aim of the present paper is threefold. First, we present the theoretical description of quantitative evaluation of diffracted waves, lateral waves and back-wall reflected waves using HFDM method. Then, we validate the range dependent frequency-domain diffracted wave amplitudes predicted from the HFDM with the GTD model calculations. Finally, the HFDM simulated ultrasonic TOFD A-scan signals for two different surface-breaking cracks with lengths 2 mm and 4 mm, respectively, in a 10 mm thick aluminium specimen are compared quantitatively with the experimental results.

2. Theory: simulation of ultrasonic TOFD technique using Huygens–Fresnel diffraction model

In this section, a theoretical procedure is presented to evaluate diffracted wave amplitude, lateral wave amplitude and back-wall reflected wave amplitude with and without mode-conversion based on the Huygens–Fresnel Diffraction Model [25,26]. Using the Huygens–Fresnel theory, diffraction of a monochromatic wave by an obstacle can be described quantitatively. Specifically, the diffracted wave amplitude in the shadow region is obtained through summation of secondary (virtual) sources located on the unblocked incident wave front. The above theory is employed to predict the propagation of ultrasonic wave diffraction from a crack. The model is implemented in a TOFD configuration (i.e. pitch-catch mode) involving a transmitter and receiver located on the surface of the specimen, as shown in Fig. 1. A vertical surface-breaking crack (PQ) is considered so that the plane containing the crack is perpendicular to the incident plane containing the incident and the diffracted waves. Taking the crack to have considerable width in the plane perpendicular to the incident plane and taking the transmitter and receiver beam divergences to be large in the incident plane (i.e. small footprint transducers), the geometry reduces to 2-Dimensions.

Fig. 1(a) depicts the diffraction of ultrasonic waves from the top surface-breaking crack. For this configuration, diffracted wave amplitude based on the Huygens–Fresnel concept can be obtained

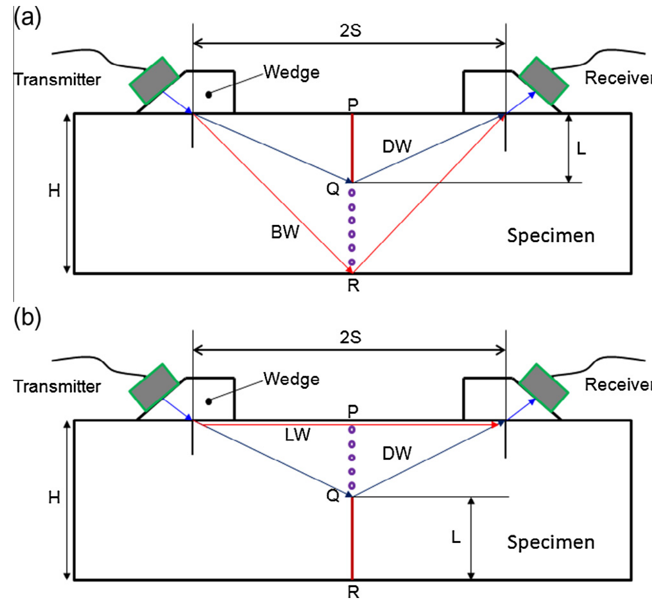

Fig. 1. Schematic of a time-of-flight diffraction (TOFD) measurement configuration showing (a) the top and (b) bottom surface-breaking vertical cracks. The crack-tip diffracted wave (DW), the back-wall reflected wave (BW), and the lateral wave (LW) are indicated.

by a summation of virtual sources in the section QR. Fig. 1(b) shows the diffraction of ultrasonic waves from the bottom surface-breaking crack. For this geometry, diffracted wave amplitude based on the Huygens–Fresnel concept would be obtained by a summation of virtual sources in the section PQ. Additionally, in this geometry, the lateral wave amplitude can also be obtained by summing over very few virtual sources located close to the top surface (i.e. in between refracted wave angles 85° and 90°). For specimen thicknesses usually encountered in experimental investigations, summation of virtual sources can be performed easily with very little computational burden.

The model uses the well-known far-field displacement expressions derived by Miller and Pursey [1] to define the virtual sources. Although these expressions have been derived for a line source, it has been extended in a straightforward manner to deal with finite aperture transducers in the form of array of line sources. The refracted ultrasonic beam due to a wedge-mounted transducer is modelled by determining the phase delays in the wedge and resolving the array of line loads on the specimen surface appropriately.

2.1. Diffracted signal amplitude calculation

For a time-harmonic line load on the free surface of a semi-infinite isotropic solid, Miller and Pursey [1] have derived the expressions for displacement at any point inside or on the surface of an elastic medium. The far-field radial and tangential displacement components for a normal line load at a frequency ω are given by [1]

$$u_r^n = \frac{ae^{i\left(\frac{3\pi}{4}-k_1R\right)}\sqrt{\frac{2}{\pi R}}(\mu^2 - 2\sin^2\theta)\cdot\cos\theta}{C_{44}F_0(\sin\theta)}, \tag{1}$$

$$u_\theta^n = \frac{ae^{i\left(\frac{5\pi}{4}-k_2R\right)}\sqrt{\frac{2\mu^5}{\pi R}}\sqrt{\mu^2\sin^2\theta - 1}\cdot\sin 2\theta}{C_{44}F_0(\mu\sin\theta)}. \tag{2}$$

The far-field radial and tangential displacements for a tangential line load are given by