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An alternative Ultrasonic Time—of—Flight Diffraction (TOFD) method

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ABSTRACT

In this work an alternative TOFD method is presented, capable to detect and size defects in the inspected material with good precision. It was shown that the diffraction used in this technique is the most relevant signal among the longitudinal backwall and the shear backwall echoes, compared to other TOFD methods. The proposed technique showed to be particularly efficient in cases where the coventional TOFD method does not perform well; cases include near-surface defects, cracks under compressive stress and bottom tip of defects. The test configuration and a mathematical description referred to the wave path of the signal of interest is described and confirmed by numerical simulations and dynamic and static tests. The proposed method was tested for different defect depth location and find industrial applications such as inspection of cracks in tubes, closed cracks and weld joints. It opens a new possibility for TOFD based inspections.

1. Introduction

Non-destructive testing (NDT) methods play a big role in structural integrity monitoring and calculations of remaining life-time of components and structures. With NDT is possible to evaluate properties and flaws of materials without compromising their functionality and usability. In this field ultrasonic techniques are used for detecting, imaging and estimating the size of flaws, being popular in many industrial applications [1].

The Ultrasonic Time-of-Flight Diffraction (TOFD) was first reported by Silk and Lidington [2] as a method that focus on diffracted waves, bringing many advantages in flaw assessment towards the previous conventional ultrasonic techniques, based mostly on reflected waves.

Over the years the conventional TOFD technique proved to be a sensitive and accurate method for through thickness sizing of discontinuities such as weld defects and fatigue cracks for a variety of materials, geometries and applications. It's resources made TOFD the first choice of NDT tool in some applications [3–7].

Advances in post-processing of signals improved reliability of the technique. Examples include methods for de-noising weak diffractions, enhancement of signal time resolution, automatic pattern recognition and classification with images and Artificial Neural Network [8–11]. TOFD simulations helped to understand the diffraction phenomena and to design inspections, predicting signal amplitude and arrival times in different setups [12,13].

At the same time the conventional TOFD weaknesses inspired the development of alternative TOFD techniques [14–18]. Among them are the ”one-skip” TOFD method [14], the ”TOFDW” method [15], shear wave TOFD (S-TOFD) [16] and immersion TOFD (I-TOFD) [17].

In this paper, a new method is proposed based on a specific mode-converted diffraction scheme, effective to measure defects located near to the inspection surface, bottom edges of internal cracks and cracks under compressive stress. Comparison with other techniques, features and potential applications of the method are illustrated and discussed in the text.

The next section presents a brief review of the conventional and alternative TOFD methods, followed by the description of the new proposed method, including the equations for calculating the defect depth for centralized and non-centralized scatterers. In later section simulation of the proposed technique is shown and verified by the experiments section, where the proposed method is tested and compared for growing cracks, cracks under compressive stress, cracks near the inspection surface and applied to a welded tube. The discussion and conclusions are presented in the last section.

2. Literature review

2.1. Conventional TOFD

The conventional TOFD method allows detecting and measuring a discontinuity in a component by transmitting a longitudinal ultrasonic wave into the material and measuring the arrival time of the first

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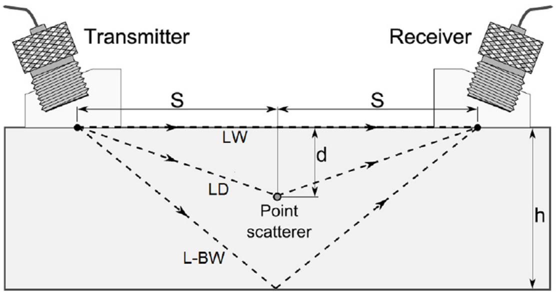

Fig. 1. Conventional TOFD setup with indicated wave paths used for depth calculations of the discontinuity edge marked as a point scatterer. Wave indications: lateral wave (LW); L-diffraction (LD); L-backwall echo (L-BW).

longitudinal diffracted wave produced in the edge of a discontinuity.

For the measurements commonly two transducers are used, one as a transmitter and one as a receiver. The basic setup, with a flaw equidistant to the transducers, is presented in Fig. 1). The first wave signals to arrive to the receiver are:

- the subsurface lateral wave (LW),
- the diffracted longitudinal wave (L-diffraction) at the edge of a discontinuity (can be considered as a point scatterer),
- the longitudinal backwall echo (L-BW).

An example of the expected received signal obtained from the setup shown in Fig. 1 is shown in Fig. 2, where all described signals are marked with descriptive symbols. The arrival time of the L-diffraction of any flaw depth has a value between the arrival time of the LW and the L-BW echo.

Considering a defect in an isotropic material located equidistantly to point-like transducers - separated by a distance $2S$ - the transit time of the L-diffraction signal t_{Ldiff} is:

$$t_{Ldiff} = \frac{2\sqrt{S^2 + d^2}}{c_l^2} \tag{1}$$

where: d denotes the depth of the point scatterer and c_l, the longitudinal sound velocity in the material.

The measured arrival time include, however, the probe delay, that is the wave propagation time outside the tested material (wedge, probe assembly, coupling media, etc), where the sound velocity is different from the inspected object.

One method to eliminate this term and calculate the defect depth is to subtract the L-diffraction wave signal and another reference signal [4]. Using the LW as reference, the arrival time differences, also represented in Fig. 2, gives Δt:

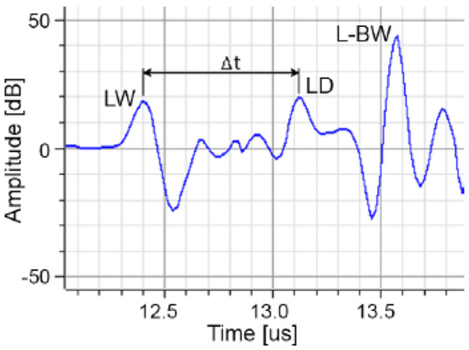

Fig. 2. Example of the expected A-scan echogram for a situation described in Fig. 1. LW and BW arrival times limit the value of the L-diffraction (LD) arrival time in conventional TOFD method.

$$\Delta t = T_{Ldiff} - T_{LW} = (t_{Ldiff} + t_{PD}) - (t_{LW} + t_{PD}) = \frac{2\sqrt{S^2 + d^2}}{c_l} - \frac{2S}{c_l} \tag{2}$$

where: T_{Ldiff} and T_{LW} denote the measured arrival time of L-diffraction wave and the lateral wave, respectively. Extracting d gives the depth of the edge of the defect:

$$d = \sqrt{\frac{c_l^2 \Delta t^2}{4} + Sc_l \Delta t} \tag{3}$$

The model presented above will present a good accuracy if the defect edge location is in the far field of the refracted wave beam and close to its central axis. A common practice for calibrating the probe assembly configuration is to use the LW signal and the L-BW signal as references in the work piece, with known thickness and ultrasonic velocity. Calibration blocks may also be used [4].

In practical inspections a defect in the workpiece is not always equidistant to the probes. In these cases the equidistant position can be achieved by moving the probe assembly laterally until the arrival time of the L-diffraction wave achieves the minimum, since this position coincides with the shortest wave path for this wave. An alternative way to find the defect tip position is to use a third probe and cross the information of one transmitter and two receivers.

If the length of an internal crack-like discontinuity is required then the arrival time of the L-diffraction wave at the second edge is needed for calculations and the same equations can be applied. This signal is only recognizable if not superposed with the first L-diffraction signal (see the following subsection).

2.1.1. Conventional TOFD limitations

Inefficiency and wrong measurements are among the conventional TOFD limitations. In some causes they can be caused by the ”dead zones” and by compressive stresses on cracks. The LW dead zone is the region in the workpiece starting at the inspection surface until certain depth where the L-diffraction signal of a flaw is not recognizable in the resulting A-scan. The cause of this effect is the LW signal amplitude and duration time, causing interference with a L-diffraction signal from a near-surface defect [19,20]. The depth of the LW dead zone, D_{ds}, is given by Ref. [21]:

$$D_{ds} = \sqrt{\frac{c_l^2 t_p^2}{4} + Sc_l t_p} \tag{4}$$

where: t_p denotes the pulse duration of the LW until 10% of the maximum peak amplitude.

According to the equation presented the dead zone depth grows with increasing probe separation. The LW dead zone is the main cause for the poor resolution of near-surface defects in the conventional TOFD method.

In the same way as the LW, a diffraction wave from the upper tip of a defect also produces a dead zone. The depth of the defect tip dead zone D_{dd} is given by:

$$D_{dd} = \sqrt{\frac{c_l^2 (t_{Ldiff} + t_p)^2}{4} - S^2 - d} \tag{5}$$

This dead zone affects the detection of signals close to this tip, e.g. hiding the bottom tip L-diffraction signal of small defects or hiding the real crack tip under compressive stress.

Compressive stress in components arise from many reasons. In some cases they are designed in the projects to prevent fatigue crack nucleation, as in rail tracks. In other cases they are present when in-service stresses and heat are ceased temporarily for inspection.

In the presence of a crack, compressive stress forces contact between the walls of the crack, resulting in less discontinuity, less scattering (more transmission) and multiple sources and lower amplitudes of diffracted waves. Combined with the diffraction dead zone effects the practical results are possible inefficient signal recognition and

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