Multiple inspection: A novel method in nondestructive evaluation

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Abstract

Nowadays, in industrial world, time reduction and accuracy increments are high important issues. Development of innovative technologies provided conditions to ensure performance of industrial components in more accurate results and also shorter time. Ultrasonic phased array system has a great influence on nondestructive evaluation of materials. This work presents a finite element simulation of a novel method based on a high ability of ultrasonic phased array system to reduce time of inspection and show more comprehensive information. Phased array capability for angle variations of wavefront when gathering with powerful Rayleigh wave generation provides multiple nondestructive testing inspection technique. Multiple inspection is a new method in order to inspect the surface and also internal bulk of work piece simultaneously.

Keywords: Multiple inspection; Finite element modelling; Ultrasonic phased array; ToFD testing

1. Introduction

Obtaining ultrasonic signal which determines planar and surface defects simultaneously is a smart and novel idea. In recent years a lot of attempts done by various methods in order to achieve this purpose. [1] [2] But in this paper for the first time, multiple inspection simulation in order to detect surface defect and internal crack has been done with reliable results. Simulation is the first step in the modeling of UT which help in gaining a better understanding of test process. The model can also predict the test results and provide a basis for choosing the optimum parameter setting and representation of the physical system in a mathematical form that can produce a response similar to that of the physical system to any changes in input parameters.. FE ultrasonic modeling first reported by LUDWIG and LORD [3] Phased array testing simulation has a significant influence for improving the PA transducers characteristics in optimizing and discovering the Favorable inspection intervals.

In recent years, Time-of-flight Diffraction (ToFD) technique has received much attention due to its potential for accurate planar and internal flaws. The ToFD technique is based on the measurement of time-of-flight of waves diffracted from flaw tips. Therefore, instead of the conventional measurement of amplitude, it works on the basis of measurement of time. ToFD provides the highest possible accuracy in measuring the depth and also length of defects. Finite element simulation of TOFD has been reported by Baskaran, et al [4]. And also Honarvar and khorasani [5]. In the case of surface cracks the most appropriate method for ultrasonic inspection of surfaces is the use of surface waves [6]. This type of waves presents some unique characteristics that make them useful for the detection and the characterization of surface discontinuities. Rayleigh waves propagate near the free boundary of a solid and decay with depth. The fact that their energy is concentrated in a small layer in the vicinity of the surface makes them particularly sensitive to small surface discontinuities. Another unique feature of these waves is that they follow complex curvatures, often providing insight to defect areas that are inaccessible to other wave forms. Date et al. [7] demonstrated the high accuracy of the ultrasonic timing method using Rayleigh waves for the characterization of slots down to 0.8mm deep (standard deviation smaller than 0.1mm). Hévin et al. [8] determined the depth of surface cracks in concrete with an accuracy of 15% using spectral analysis of the directly transmitted wave. Scala
and Bowles [9] performed measurements of slots as small as 0.5 mm in depth on the basis of transmitted
near field measurements with an accuracy better than 50µm.

2. FEM Modelling of TOFD Method

The commercial FEM package ABAQUS6.11 is used for two-dimensional modelling of ultrasonic wave
propagation. The physical properties of the block are as follows: E = 60 GPa, ρ= 2240 kg/m3, and v= 0.244. The entire area of the sample is discreticised into a standard two-dimensional spatial square plane
strain elements (CPE4R) with linear shape functions and four nodes, where each node has two degrees of
freedom with respect to displacement. In order to get more accurate results, we can decrease element size
but there are limitations. These limitations occurred due to limited computer system capacity to calculate
an enormous calculation needed for simulation. By the previous work [10], mesh size (Δd) should satisfies
to equation (1):

\[ Δd \leq \frac{λ}{15} \]  

Where \( λ_{\text{min}} \) is the shortest wavelength at the excitation frequency of the simulated waves and Δd is the
dimension of the element. Our trial and error studies showed that in order to have a low computation time
and good convergence, a mesh size in the order of 5x10-5 m should be chosen.

2.1 Modeling of transmitting transducer: In this study actual piezoelectric mechanisms has been
modeled by the relevant transient pressure excitation. This excitation is a narrowband tone burst pulse of a
certain frequency which is applied on the 0.3mm distance on a top surface of sample block. 32 elements
designed and excited, In other words Ultrasonic pulse was introduced as a transient excitation pulse which
applied as pressure on width of each element. This pulse is given in equation (2) where f is the excitation
frequency and N is the number of cycles force.

\[ F = \left[ 1 - \cos \left( \frac{2\pi f}{N} t \right) \right] \cos (2\pi ft) , \quad 0 < t < \frac{N}{f} \]  

In order to propagate an oblique ultrasonic wave by phased array probe, we use a time delay law. These
time delays which applied on adjacent phased array element computed with Huygens’s principle that stated
in equation 3:

\[ Δt = \frac{d \sin θ_s}{C} \]  

Where “d” is distance between two adjacent elements, θ_s is steering angle or propagation angle, “C” is
longitudinal wave velocity in the media and Δt is time delay between two adjacent elements.

2.2 Modeling of receiving transducer: Since the basic of piezoelectric transducer operation is the
conversion of electrical pulses to mechanical pressure and inverse, therefore we consider a “set
point” on surface as receiver probe. Acceleration amplitude variations of this “set point” regarded
as amplitudes variations in simulations in order to increase accuracy and quality of simulations.

3. Convergence test

One of the most important part of validation of simulated model is “convergence test” for FEM simulation.
In order to discuss about convergence results, different size of element is considered. Amplitude diagram
of center node of probe from top crack tip is used to discuss about converging results. Signal to noise ratio
is obtained from received signals and plotted against element size in Figure 1. For elements which are
smaller than 50µm size, SN ratio is stabilized and has a constant value approximately.
4. Interaction of phased array ultrasonic waves with embedded crack

After a phased array transducer is excited, longitudinal (I) and shear (II) waves are propagated in bulk of simulated steel block. Also lateral longitudinal wave (III), lateral shear wave (IV) and Rayleigh wave (V) are transmitted along the surface. Head wave is denoted by (VI) (figure 2). After the Longitudinal wave incident to crack, sharp crack tip, like a source of wave, starting out a wave emission. These diffracted waves from crack tips applied for ToFD method, the first diffracted wave from top crack tip which denoted by “VII” is “Top Longitudinal Diffraction” wave or “TLD”. Second diffracted wave is “Top shear diffraction” wave or “TSD”, indicated by “VIII”, also bottom diffraction waves denoted by (IX) and (X) as shown in figure 3 and figure 4.

![Signal to noise ratio obtained from received signals](image1)

![Snapshot of Abaqus viewport at 5.7(µs)](image2)

![Snapshot of Abaqus viewport at 9.066(µs)](image3)
5. Effect of wave angle variation on amplitude of waves

Figure 6 is the diagram of variation of “Lateral longitudinal” wave amplitude by change in angle of wave. Slope of the curve is greater for angles which are wider than 60° in other words “Lateral longitudinal” wave amplitude increased more. For angles less than 40° “Lateral longitudinal” received amplitudes reduced too much in comparison with angles greater than 60°. Figure 6 indicates that “Lateral longitudinal” amplitudes...
is related to angle of wave significantly and if it is used for surface defect detection, then wave angle should be considered as a high limiting parameter. “Lateral shear” wave amplitude variations plotted against angle wave variations. Measured amplitudes increases by increasing the angle of oblique wave. Figure 7 denotes the high dependency of “Lateral shear” wave on wave angles. For angles which less than 45’ “Lateral Shear” wave measured amplitude has small amount and it is hard to distinguish it from noises. Figure 8 indicates the variation of Rayleigh wave amplitudes by change in angle of wave. It is obvious from this figure that Rayleigh wave amplitudes aren’t affected by angle variation of wave. According to Figure 6 and 7 which show the effects of change in wave angle parameter on received signals, it can be concluded that a single type of surface waves which is not affected by angle variations is Rayleigh wave. Rayleigh wave is not impressed considerably with angle variation and it has constant amplitudes value even for oblique waves which are smaller than 40 degree.

6. Effect of distance on amplitude of surface waves

As shown in Figure 9, the lateral longitudinal wave amplitude decreases by increasing the distance of receiving transducer from transmitter. Received “Lateral longitudinal” echo for a transducer which is located at 1cm distance from the transmitting transducer has maximum value due to short distance between
transmitter and receiver. In the first 4cm distance from transmitter, “Lateral longitudinal” wave amplitude decreases rapidly, but in the next 4cm distance, the slope of curve is much less. Figure 9 demonstrates that lateral longitudinal wave has high decreasing value specially at near distances from transmitting probe and when the “Lateral longitudinal” wave travels 8cm, its amplitude reduced significantly. “Lateral shear” variations with distance is plotted in Figure 10. After 4cm distance “Lateral shear” wave decreases significantly, between 2cm and 4cm slope of curve i.e. ratio of “Lateral shear” amplitude variations with respect to distance from transmitter transducer is greater than other parts of the curve, in other word at this area “Lateral shear” wave amplitude reduced a lot. “Lateral shear” and “Lateral longitudinal” wave amplitude decrease a lot after passing 6cm and 8cm respectively. It is a warning notation in surface defect detection. If defects locate out of this zone (6cm and 8cm from transmitting transducer), using “Lateral longitudinal” and “Lateral shear” waves for defect detection have not recognizable results. Figure 11 shows the relation between Rayleigh wave amplitude and Rayleigh wave travelling distance. Rayleigh waves aren’t affected by distance variations. It has constant amplitudes even in far distances which other types of surface waves disappear. In addition to positive feature which stated at previous section, Constant amplitude of Rayleigh wave with distance variations is another main positive aspect of Rayleigh waves for surface defect detection.

7. Crack sizing by ToFD with single probe technique in various depths

![Figure 12: Crack sizing by TOFD with single probe technique in various depths](image1)

![Figure 13: the variation of relative error for crack sizing by TOFD method with single probe in different depths](image2)
Figure 12 shows his method schematically. Crack depth varies from 10mm to 75mm. Crack length is 7mm and is perpendicular to scanning surface. Normal distance between centerline of probe and crack body(S) is 2.5cm. Cracks were located in 1,2,3,4,5,5.5,6,6.5,7,7.5 far from surface and normal distance between cracks and centerline of probe is 2.5cm. Diffracted waves from crack tips were detected well and the A-scan was analyzed, results are show in Figure 13. A-scan signals a sample block with embedded crack in depths 2 shown in figure 14. all received echoes before 4(µs) which spreads on time axis are initial pulses(V) and appear due to phased array excitation pulses on center node of probe. In Figure 4-30 four main diffraction signals are observed on received signal. In Figure 14 the Top longitudinal diffraction (I) and the Bottom longitudinal diffraction (II) are received at 11.088(µs) and 12.680(µs) and define a crack size with 3.9% error. Shear diffraction signals are sensed after longitudinal diffraction waves.

8. **Multiple detection of surface and planar defect**

Effect of angle variation and also increasing distance on surface waves has been discussed in the section of Rayleigh wave, from two main aspects Rayleigh wave is in priority for surface defect detection. At first Rayleigh wave constant amplitude by increasing distance motivate us to applying this wave for defect detection, another aspect is amplitude stability by angle variations. ToFD with single probe simulated completely. In this section, single probe is used as the both transmitter and receiver probe for nondestructive evaluation of crack and surface defect detection simultaneously for the first time. A-scan received signal clearly shows the crack diffraction echoes and also Rayleigh reflection waves. Finally an A-scan which determine defects and also characterize internal crack is obtained. Figure 15 (a) shows A-scan of sample which has a crack of 1cm length in 2cm depth and also surface defect in 22.14cm far from the center of phased array transducer. Figure 15 (b) and (c) is magnifying view of first 40(µs) and last 40(µs), reflected and diffracted waves can be observed in figure 15(a), because of long A-scan time, parts of it, is enlarged.
In first 40(µs), embedded crack is detected by ToFD method and evaluation of diffraction received echoes indicates a crack of 9.5mm length which has 4.2% error.

Accuracy of Rayleigh wave in surface defect detection shown on figure 16. The error growth rate variation is minus and low and also after defect distance from probe is increased to 18cm, it descend more

9. Conclusions
Between surface waves, Constant amplitude indicates the Rayleigh wave stability on surface. It keeps energy even in far distances which other types of surface waves disappear. Also a single form of surface waves which is not affected by angle variations is Rayleigh wave.

Error variations of TOFD by single probe for crack with constant length in different depths investigated. From depth 1 to 6 cm, a good approximation of crack size obtained. The critical depth range for crack size evaluation is 6 to 8cm in this method.

Simulation of Multiple defect detection, a novel method in defect detection and evaluation which determines an internal crack and surface defect simultaneously has been done, this method based on high capabilities of ultrasonic phased array system.

Accuracy of Rayleigh wave in surface defect detection determined and surface defect detected in 24cm distance by less than 10%.

References


