Simulation of Time-of-Flight Diffraction (ToFD) Technique by Finite Element Method

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Abstract
Time-of-flight Diffraction (ToFD) is an ultrasonic nondestructive testing technique used for detection, sizing and evaluation of discontinuities. The ToFD technique, which is based on the diffraction phenomenon, is usually applied to thick sections (> 15 mm). In this paper, we use the Finite Element Method (FEM) for modelling the ToFD technique in a two-dimensional geometry. Ultrasonic waves are generated in samples with different types of notches and the interaction of waves with these notches is monitored. This study does not only provide a better understanding of the diffraction phenomenon but can also help in design and implementation of new test procedures for examination of industrial parts. One major application would be using the ToFD technique for testing thin sections in pressure vessels and pipes.

Keywords: Ultrasonic testing, Time-of-flight diffraction (ToFD), Wave propagation, Finite element method

1. Introduction

Ultrasonic testing techniques have been quite successful in detection and sizing of both internal and surface defects. The conventional ultrasonic pulse-echo technique uses the pulse transit time for locating the flaw and the echo amplitude for sizing it. The amplitude of the back-reflected wave is not always sufficient for accurate flaw sizing. This is because the amplitude of the reflected pulse can be influenced by many parameters other than the size of the reflector. Such parameters include the surface roughness, transparency, and orientation of the defect [1]. In recent years, Time-of-flight Diffraction (ToFD) technique has received much attention due to its potential for accurate sizing of 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. Compared to purely reflection-based techniques, the ToFD technique, which is based upon diffraction as well as reflection, is less sensitive to the angle of incidence with respect to the orientation of the discontinuity. ToFD provides the highest possible accuracy in measuring the depth and through-wall length of defects [2].

The complexity of the equations governing the propagation of ultrasonic waves in solid materials, especially when the specimen under investigation has a complex geometry, forces the researchers to look for alternative numerical modelling approaches [3]. Numerical modelling provides 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. Finite element method (FEM) is a numerical solution technique which can be used for this purpose.

Finite element simulation of ultrasonic wave propagation and its interaction with defects have been studied by Ludwig and Lord [4]. Simulation of the ToFD technique using finite element method has been carried out by Baskaran et al. [5]. They used the finite element package ANSYS to model the propagation of ultrasonic waves in a thin cracked two-dimensional specimen. The software package ANSYS uses the implicit Newmark's algorithm
to solve the transient wave equations. The numerical analysis of wave propagation for ToFD in an austenitic stainless steel specimen with consideration of the effects of scattering at grain boundaries was carried out by Lin et al. [6]. They developed an efficient method for modelling the effects of coarse grains in austenitic materials.

Depending on the strategy used to convert the differential equations into algebraic equations, finite element methods can be divided into explicit and implicit types. In explicit types, the value of a variable such as displacement at a certain time is determined based on its known values at earlier time steps. On the other hand, in implicit algorithms, values of variables at future time steps are needed to determine their current values. Implicit methods are more complex to program and require more computational time for each time step. Explicit methods are easier to program. However, they demand smaller time steps compared to implicit ones. For problems involving dynamic phenomenon such as ultrasonic wave propagation, where instantaneous results at each time step are required, explicit methods are preferred [7].

In this paper, the explicit type of finite element method is used for simulating the interaction of ultrasonic waves with boundaries in an ultrasonic time-of-flight diffraction (ToFD) testing configuration. The finite element package ABAQUS is used to model the propagation of ultrasonic waves in a two-dimensional geometry. This study provides a better understanding of the diffraction phenomenon and interaction of ultrasonic waves with discontinuities. It also helps in the design and setup of ToFD testing measurements, especially when dealing with thin sections.

2. Modelling of wave propagation

The commercial FEM package ABAQUS is used for two-dimensional modelling of ultrasonic wave propagation in samples made from glass and steel. The entire area of the sample is discreticised into 4-node 2D plane strain elements. Choosing the correct element size is a crucial issue in studying the wave propagation by finite element modelling. Choosing the correct size of elements reduces the computation time while maintaining the required accuracy of the results. 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 $5 \times 10^{-5}$ m should be chosen. This provides at least ten elements for the smallest propagating wavelength present in the ultrasonic pulse.

To verify the FEM modelling process, first we consider the interaction of ultrasonic waves with a 5 mm side-drilled hole in a glass sample. The physical properties of the block are as follows: $E = 60$ GPa, $\rho = 2240$ kg/m$^3$, and $\nu = 0.244$. The reason for choosing a glass sample is because we can visually monitor the propagation of the wave inside this sample by using a photoelastic imaging system.

Figure 1. Glass specimen with a side-drilled hole.

Figure 2 shows six snapshots of the ultrasonic pulse, generated by a 2 MHz, 45 degrees angle beam shear probe. These photos are taken during the propagation of the ultrasonic pulse through the glass sample and its interaction with the side-drilled hole.
The propagation of an ultrasonic pulse through the glass specimen was also modelled by the finite-element method. In the FEM model, the ultrasonic pulse was introduced as a transient excitation pulse inserted on a finite number of nodes on the top surface of the sample. This excitation is equivalent to the pulse generated by the ultrasonic piezoelectric transducer. The transient excitation pulse used for modelling the piezoelectric mechanism is given by the following equation [5],

\[
Y(t) = \begin{cases} 
1 - \cos\left(\frac{2\pi f}{N} t\right) \sin(2\pi f t), & \text{for } 0 \leq t \leq \frac{N}{f} \\
0 & \text{otherwise}
\end{cases}
\]  

where \( f \) is the excitation frequency and \( N \) is the number of cycles. In the current FEM model, the frequency is 2 MHz and \( N = 2 \). The pulse used in this simulation is shown in Fig. 3.

Figure 2. Snapshots taken by a photoelastic unit showing the ultrasonic pulse propagating through the glass specimen and its interaction with a side-drilled hole.

Figure 3. The two-cycle pulse of 2 MHz centre frequency used for excitation of ultrasonic waves in the glass sample.
This initial displacement is applied to the nodes that are located at the transmitter domain as shown in Fig. 1. The beam can be angulated at 45° by introducing time delays into the excitation signals applied at different surface nodes. Using FEM results, six snapshots are prepared at time intervals which are almost the same as those used in Fig. 2, see Fig. 4. Comparing Figs. 2 and 4, we observe that the images obtained from FEM simulations are in very good agreement with those obtained by the photoelastic system.

![Figure 4. Finite element modeling of the propagation of a 2 MHz, 45° angle shear wave through a glass sample and its interaction with a side-drilled hole.](image)

### 3. Modelling of the ToFD technique

In this Section, we present results obtained from FEM modelling of the ultrasonic ToFD technique in steel specimens having surface and internal cracks. The first sample has a surface crack on its top surface as shown in Fig. 5. This block is 50 mm long and its height is 10 mm. The surface breaking crack is 4 mm long and has a width of 0.1 mm. The material is carbon steel for which the Young's module, mass density, and Poisson ratio are 207 GPa, 7850 kg/m³ and 0.3, respectively.

![Figure 5. Steel sample with a surface crack on top surface.](image)

The input ultrasonic pulse used in this simulation has a centre frequency of 5 MHz and its number of oscillations is equal to 3, see Fig. 6.
Once again 4-node, 2D plane strain elements are used for meshing this steel block. Figure 7 shows snapshots taken from the specimen at 2, 3, and 5 µs. In Fig. 7, it can be observed that when the excitation is applied on the surface, longitudinal and shear waves are generated inside the material and a lateral wave propagates on the surface. The longitudinal and shear waves enter into the material at angles of 45 and 22 degrees and are reflected and mode converted upon striking the back surface. Diffracted waves are generated at the crack tip when the longitudinal wave interacts with the crack. Because of the surface breaking crack, the lateral wave can not reach the receiving transducer and only the diffracted and backwall reflections can be picked up by the receiving transducer. Figure 8 shows the received signals where the first echo is the result of diffraction of longitudinal waves from the crack tip and the second echo is the backwall reflection.
Figure 8. The ultrasonic signal received at the receiving transducer in FEM simulation of the steel block with a crack open to the top surface.

For the second sample, the crack is located inside the block as shown in Fig. 9. The dimensions of the block and crack are the same as before. Figure 9 shows snapshots taken from this specimen at 3 and 3.33 µs. The generation of diffracted waves from the top and bottom tips of the crack can be clearly observed in Fig. 9. The signal received at the receiving transducer is shown in Fig. 10. In Fig. 10, the first echo is the lateral wave and the last echo is the backwall reflection. The tip-diffracted echoes lie somewhere between these two echoes. We notice that the tip diffracted echoes cannot be easily discriminated from other echoes and this is something very common in real ToFD measurements. Various signal processing techniques can be used to overcome this problem.

Figure 9. Two snapshots of the interaction of the ultrasonic wave with an internal crack inside the steel block.

Figure 10. The signal received at the receiving transducer for the second sample. The first echo is due to diffraction of longitudinal waves from the crack tip and the second echo is the backwall reflection.
The third sample contains a crack open to the back surface. The dimensions of the block and crack are the same as before. Figure 11 shows two snapshots taken from this specimen at 3.16 and 3.33 µs. The signal received at the receiving transducer is shown in Fig. 12. In Fig. 12, the first echo is due to the lateral wave and the second echo is the diffracted wave from the crack tip.

![Figure 11](https://via.placeholder.com/150)

Figure 11. Three different snapshots showing the interaction of the waves with a surface breaking crack in a steel block.

![Figure 12](https://via.placeholder.com/150)

Figure 12. The ultrasonic signal received at the receiving transducer in FEM simulation of the steel block with a crack open to the back surface.

### 4. Conclusions

The propagation of ultrasonic waves was simulated using finite element method (FEM). Explicit integration solution technique was used in order to reduce the computation time and save on memory and disk space. Four different samples were considered in this paper. All samples were meshed by 4-node 2D plane strain elements. The first sample was a rectangular block made from glass and had a side-drilled hole in the middle. The other three blocks were made from steel. The ToFD technique was simulated on these blocks and the interaction of the ultrasonic pulses with surface and internal cracks were demonstrated. The signals received at the receiving transducer were plotted for these simulations. These signals are similar to the signals commonly obtained in actual ToFD measurements. This study provides a better understanding of the diffraction phenomenon in ToFD measurements and can also be very useful in design and implementation of new ToFD testing procedures.
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References