Finite Difference Time Domain Simulation of Ultrasonic Phased Array Sector Scan for Imaging Embedded Defects in Blocks and Elbows

L. Satyanarayan, K.V. Mohan, C.V. Krishnamurthy and K. Balasubramaniam

Center for Non-Destructive Evaluation, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai-600 036
e-mail: balas@iitm.ac.in

Abstract

This paper reports the simulation of phased array ultrasonic wave propagation using Finite Difference Time Domain (FDTD) method to image crack like defects in Aluminum Blocks and Stainless Steel elbow sections. Inclined crack like defects have been considered for the simulation. Experiments were also performed on an Aluminum block with inclined embedded cracks various sizes in order to validate the results of the simulation. The simulation studies were then extended to imaging embedded cracks in an elbow section.

Keywords: *Phased array, Sector scan, Crack imaging, Elbow sections, Embedded cracks*

1. Introduction

Pressure vessels and piping components used in power plants invariably use SS pipe and elbow sections. These components are subject to mechanical/thermal loads and as a consequence of which may develop cracks. It becomes very important to accurately size these defects to ascertain the structural integrity and hence calls for a reliable NDE technique [1, 2].

Traditionally, ultrasonics has been used to image and size the defects. But, due to certain inherent disadvantages in conventional ultrasonics such as beam divergence and inability to quickly vary the angle of the beam for inspection, it becomes difficult to rapidly carry out inspection of the component. The phased array ultrasonic technique offers tremendous flexibility to focus and steer the beam to the required point and angle respectively [3-6]. The versatile sector scan mode of the phased array inspection allows us to sweep through an angular range for rapid inspection of a large area. The phased array technique can be used to quickly ascertain the presence of a defect and image it. The objective of this paper is to simulate the sector scan feature of the phased array using FDTD method and to image embedded inclined crack like defects in an aluminum block and validate the simulation results by comparing with experimental sector scans.

One advantage of modeling using the FDTD method is that complex structures with defects of various configurations can be handled easily where it would be difficult to conduct experiments [7]. The model was then extended to imaging and sizing of a 45 degree crack like defect in an elbow specimen. Figure 1 shows how a beam can be steered at an angle in a specimen with a crack like defect that is computed using Finite Difference Time Domain method (FDTD).

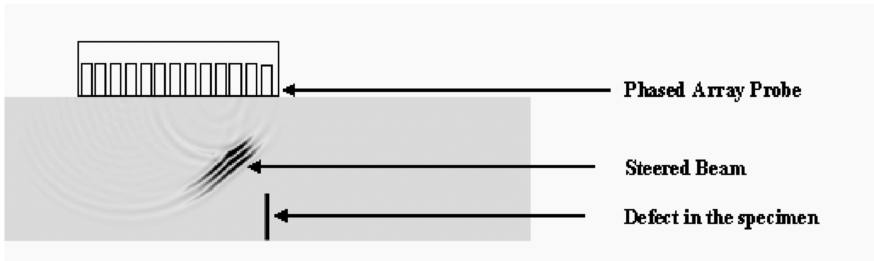


Fig. 1: Beam steering and focusing in a phased array transducer

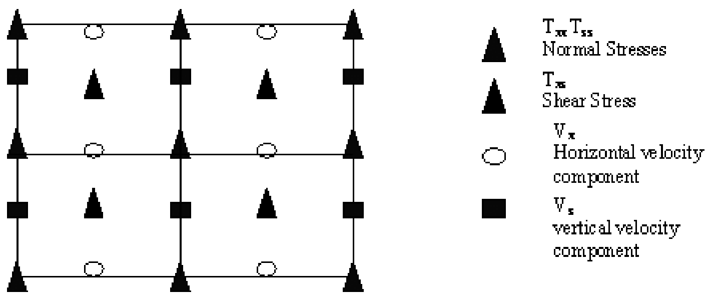


Fig. 2: Finite difference grid of the domain showing the positions of each field variable

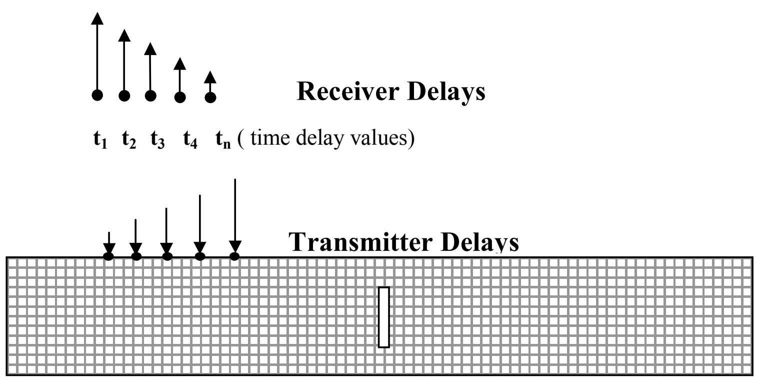


Fig. 3: Finite difference model for phased array transmission and reception

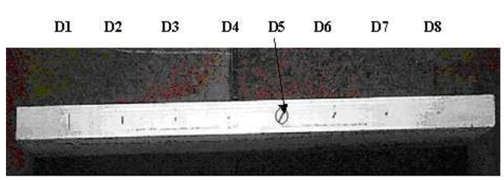
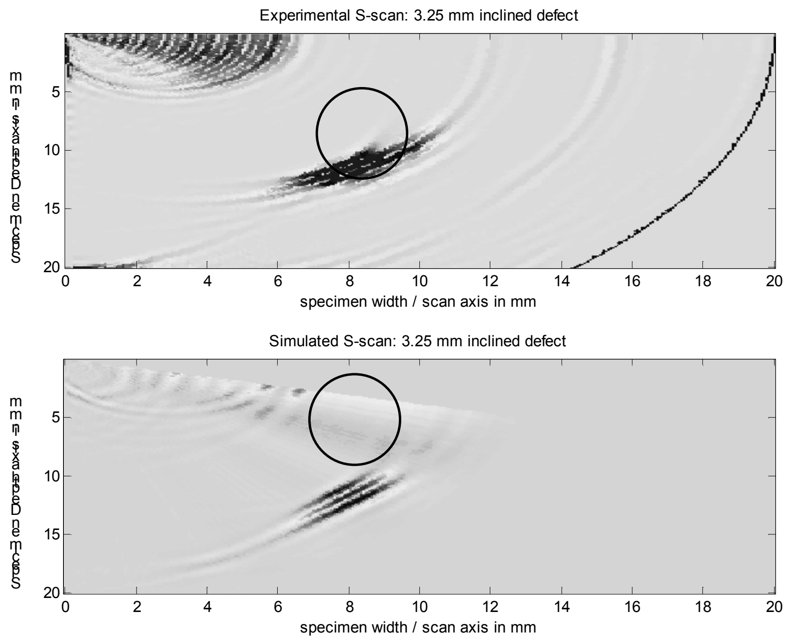
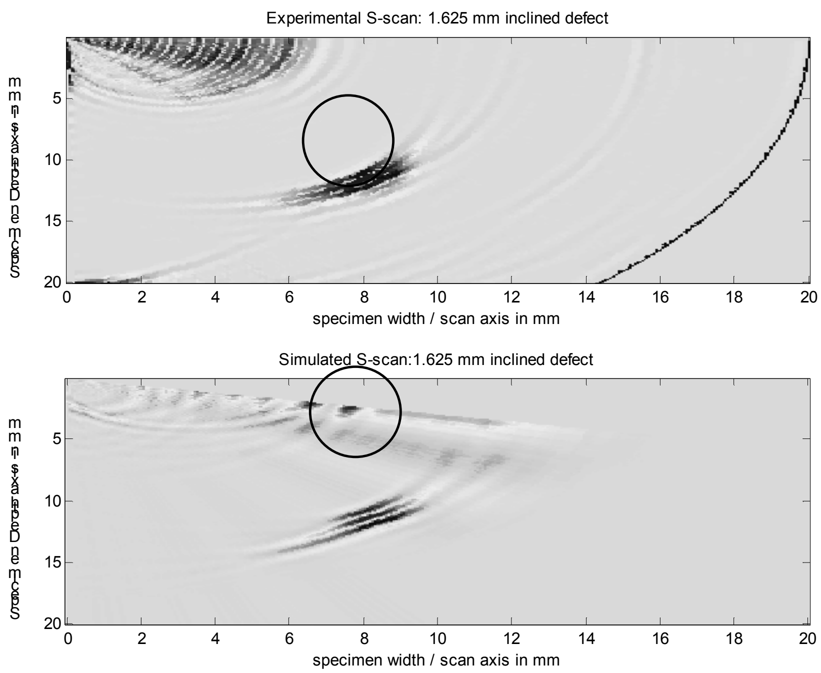


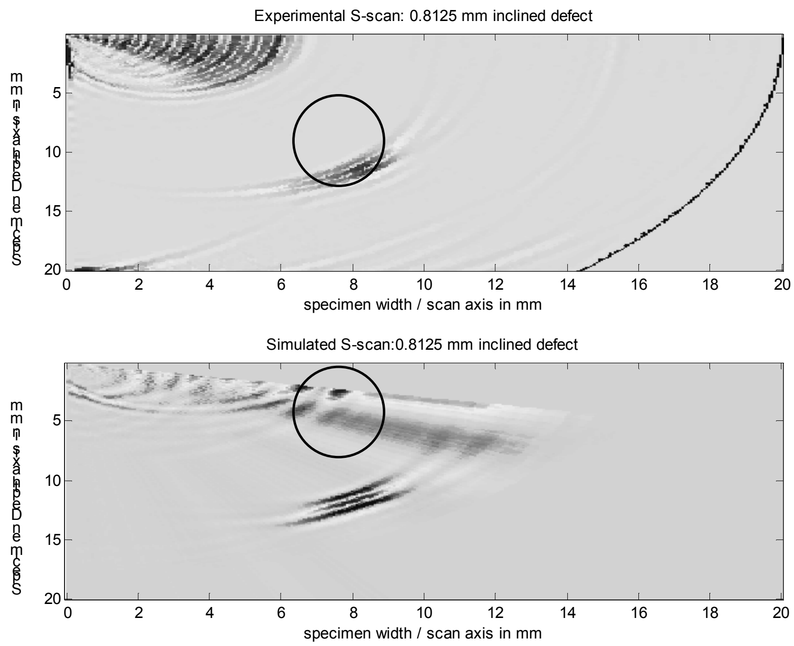
Fig. 4: Aluminium plate sample with simulated defects



(a) 3.25 mm Inclined defect



(b) 1.625 mm Inclined defect



(c) 0.8125 mm Inclined defect

Fig. 5: Comparison of experimental and simulated S-scans of 45 inclined defect in Al block

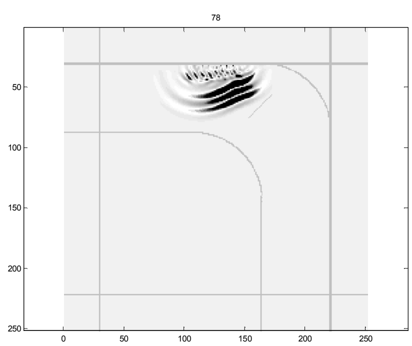


Fig. 6: Phased array wave propagation in an elbow and its interaction with an inclined defect

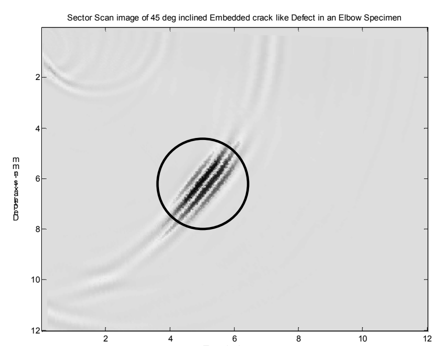


Fig. 7: Sector Scan image of 45 deg inclined embedded crack like Defect in an Elbow Specimen

Table 1: The details of vertical EDM notches and their sizes of 13 mm thick aluminium sample

Defect Number	Type	Length(mm)	Thickness(mm)	depth (mm)
D6	45° Inclined Slot	6	0.5	3.25
D7	45° Inclined Slot	6	0.5	1.62
D8	45° Inclined Slot	6	0.5	0.81

Table 2: Comparison of the notch sizes obtained by amplitude drop method on 13 mm thick Aluminium Block sample

Defect Number	Actual Depth (mm)	3 dB drop method (mm) :simulated	Percentage Error : simulated	3 dB drop method (mm) :experimental	Percentage Error : experimental
D6	3.2	3.4	-6.25%	3.5	-9.37%
D7	1.6	1.8	-12.5%	2.0	-25.0%
D8	0.8	0.9	-12.5%	1.0	-25.0%

Table 3: Comparison of the crack size obtained by amplitude drop method on 12 mm thick SS elbow sample

Defect type	Actual Depth (mm)	3 dB drop method (mm): simulated	Percentage Error : simulated
Embedded Inclined Crack	3.2	3.4	-6.25%

2. Finite Difference Time Domain Formulation of the Problem

The FDTD model for the simulation and visualization of the elastic wave propagation is based on a first order velocity-stress finite-difference method for homogeneous isotropic material [8]. The equation of motion, the stress-strain relation together with constitutive equations completely describes the elastic wave propagation in a homogenous material.

The differential equations are discretized by finite difference scheme which are obtained by truncating Taylor series expansion. The finite difference discretization of the set of equations leads to a staggered finite difference grid as shown in Figure 2. Here the normal stresses namely τ_{xx} and τ_{zz} are represented at a single node and the remaining field (velocity) variables, v_z and v_x and the shear component τ_{xz} are represented in the grid at half spatial steps to each other.

Appropriate boundary conditions need to be applied while implementing the FDTD technique to define the defect and the specimen boundaries. A variety of techniques are available to apply a free boundary condition for staggered grid FDTD schemes. In this study, the velocities along the back wall and the defect boundaries was set to zero [9] i.e., u=0; v= 0.

During modeling, in order to reduce the computational resource requirements a sub-domain region of the specimen is used. This domain process creates artificial free boundaries that lead to undesirable reflections and mode conversions that do not occur in the experiments. In order to eliminate these artifact reflected waves, the Absorbing Boundary Conditions (ABC) was applied on the appropriate domain boundaries. The ABCs can be implemented by incorporating the perfectly matching layer (PML) boundary conditions [10]. PMLs are an extra set of layers that are incorporated outside the domain of the model whose impedance and the phase velocity matches with that of the domain and also have a attenuation function that rapidly decays the wave that proceeds though the layers. Since, there is no impedance mismatch between the PML and the domain, very little reflection occurs at the domain-PML boundary.

3. Phased Array Ultrasonic System

The Phased Array Ultrasonic experimental setup used in this study consists of the R/D Tech Omniscan MX ultrasonic Phased Array system with the array probe (Probe No. : C3-5L64) using the electronic scanning feature on the MS pipe specimen. The data presented in this paper was acquired using 5 MHz centre frequency, 64 elements (46 mm x 15 mm area) array probe. The defects were imaged by phasing the elements of the probe to generate a longitudinal wave steered at requisite angle of inspection in the linear scan mode.

4. Simulation of A-scan Signals and B-Scan Images Using FDTD Technique

A two dimensional model was developed using the FDTD technique to simulate the phased array wave propagation in rectangular block and elbow like structures. The density of the Aluminium was taken as 2700 kg/m^3 and the longitudinal wave velocity is assumed to be 6300 m/s while the shear wave velocity is assumed to be 3200 m/s. The density of the SS pipe was taken as 7900 kg/m^3 and the longitudinal wave velocity is assumed to be 5900 m/s while the shear wave velocity is assumed to be 2900 m/s.

The two dimensional model was developed in **MATLAB**® to simulate the propagation of the ultrasonic wave in the specimen of an arbitrary geometry. The code takes input parameters that define a phased array experimental setup and generates A-scans and B-scans that can be compared with the corresponding experimental A-scans and B-scans. The time delay/ focal laws [11] have been used to simulate phased array transmission and reception of unfocused phase steered beams. Figure 3 shows the finite difference model of the specimen along with the transmission and reception delay scheme applied to simulate the phased array transducer. In order to replicate the experimental conditions, the number of elements in the simulation that have been kept active was 16 for all scans and the beam was steered at 0-89 degrees to the normal with respect to the centre of the probe from an ultrasonic phased array transducer of 5 MHz centre frequency. A three cycle Hanning window pulse was chosen as input to the transducer elements for the simulations. The elements of the transducer (assumed to be point sources) generates spherical wave fronts which interfere constructively as dictated by the phase delay laws and get steered at the required angle of inspection. The grid size in the model was taken as (wavelength) $\lambda/12$.

During transmission, the nodes that represent the active transducer elements were provided displacements at time delay values given by the well known transmit delay law provided in Equation (14). Using these time delays, the wave was steered at the requisite angles within the specimen. The received signals are then time-advanced using the reception delay law and then summed together to generate the A-scan at that inspection point. The defects in the specimen are modeled as free surfaces which reflect/diffract the entire acoustic energy incident on them.

5. Specimen Preparation

Experiments were conducted on a 13 mm thick Aluminium sample with 3.2, 1.6, and 0.8 mm deep (i.e., 25%, 12.5% and 6.25% of the thickness of the specimen) 45 degree inclined EDM notches using phase steered sector scan of 0-89° angular range. The details of EDM notches are given in Table 1. The sample is shown in Figure 4.

6. Experimental Results

Figures 5(a) – (d) show the comparison of simulated and experimental S-scans. The 3 dB amplitude drop method was used to determine the sizes of the of the defects and the percentage errors associated with the experimental and the simulated values with respect to the actual defect sizes were tabulated and compared and are given in Table 2.

7. Simulation of Wave Propagation in Complex Structures (Elbows)

The wave propagation inside the 12mm thick elbow structure as simulated using the FDTD method is shown in Figure 6. The material of the elbow is assumed as Stainless Steel and the mesh size (λ/12) was selected after convergence studies. The sector scan image an inclined embedded notch in the elbow sample is given in Figure 7.

8. Summary and Conclusions

The simulation of sector scan feature of the Phased array was successfully developed using a two-dimensional FDTD model.

Simulations were carried out to image inclined embedded crack like defects in an aluminium block. The simulated Sector-scans were compared with the experimentally obtained Sector-scans. The simulated signals were in good agreement with the experimental signals.

The simulation was then extended to image an inclined embedded crack in an elbow specimen.

The model can be used to get an insight into understanding the wave path in specimens with complex geometries and optimize the experimental parameters before actually conducting the experiment.

9. Acknowledgements

The authors thank the BRNS for funding the project.

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