SIMULTSONIC: A SIMULATION TOOL FOR ULTRASONIC INSPECTION

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ABSTRACT. A simulation program SIMULTSONIC is under development at CNDE to help determine and/or help optimize ultrasonic probe locations for inspection of complex components. SIMULTSONIC provides a ray-trace based assessment initially followed by a displacement or pressure field-based assessment for user-specified probe positions and user-selected component. Immersion and contact modes of inspection are available in SIMULTSONIC. The code written in Visual C++ operating in Microsoft Windows environment provides an interactive user interface. In this paper, the application of SIMULTSONIC to the inspection of very thin-walled pipes (with 450 um wall thickness) is described. Ray trace based assessment was done using SIMULTSONIC to determine the standoff distance and the angle of oblique incidence for an immersion mode focused transducer. A 3-cycle Hanning window pulse was chosen for simulations. Experiments were carried out to validate the simulations. The A-scans and the associated B-Scan images obtained through simulations show good correlation with experimental results, both with the arrival time of the signal as well as with the signal amplitudes. The scope of SIMULTSONIC to deal with parametrically represented surfaces will also be discussed.

Keywords: ultrasonics, simulation, ray-tracing.
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INTRODUCTION

A well-established concept often used to aid our understanding of wave propagation is the concept of a ray. A ray picture for a specific source-object-receiver configuration, however qualitative, is a very useful construct [1]. With the advent of the computer, a more quantitative assessment of a ray picture has been made possible and has provided results often with surprising accuracy. There have been many areas ranging from optics, to radiowave communication [2], to underwater acoustics [3] where the ray picture has provided simple, intuitive and reasonably correct assessment. Even in ultrasonics, several ray-based assessments have been and are being developed [4]. At CNDE, as part of a large research program, the need to develop a ray-based assessment code for UT inspection is being addressed through SIMULTSONIC. Prediction of the time-of-arrival of a pulse, the distinction between longitudinal and shear wave arrivals, and the identification of mode converted signals are important features that a ray picture can provide with reasonable accuracy. While it is known that rays cannot model diffraction effects, it is an established practice to combine the results from geometric theory of diffraction (GTD) with the ray picture to provide a reasonable model of diffraction phenomena [5].

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SIMULTSONIC is evolving into a tool that seeks to provide a ray-based assessment of UT inspection. It employs a time-stepping scheme to launch rays from the transducer, traces its path to the nearest interface, and generates new rays at the interface satisfying Snell's law, tracks mode conversion all in a recursive manner. Immersion and contact modes of inspection can be simulated. Object shapes can be simple or complex. While simple shapes are parametrically handled, meshing is used to describe complex shapes.

RAY MODEL

Each ray is characterized by the position of its head, which is given by the global X, Y and Z coordinates. The ray also has three direction cosines that describe the direction in which the ray propagates. Each ray is also characterized by its type (whether shear or longitudinal) and its energy. The ray also has information about the amount of time lapsed from the time it was created at the transducer. The rays are generated as parallel, converging or diverging beams from the transducer as shown in Figure 1.

Ray tracing is carried out in specific time steps and checks are made at every stage to ascertain the ray position in the domain as a function of the time elapsed. Each ray is propagated until it meets an interface or has reached the end of the domain or until the given time. Once a ray meets an interface, new reflected and refracted rays are created based on the angle of incidence of the rays taking into account mode conversion. Generation of the reflected ray or the refracted ray is also governed by the critical angles, evaluated using the sound speeds in the two media. In the most general case (a solid-solid interface with incident angle below the first critical angle), four new rays are formed. These are the shear reflected and refracted rays and the longitudinal reflected and refracted rays. The incident ray can be either a shear ray or a longitudinal ray. Using the generalized Snell's law and the law of reflection and refraction (Incident ray, reflected ray or transmitted ray and the normal at the point of contact lie in the same plane), the vectors of the reflected and refracted ray are calculated.

The standoff distance of the transducer from the surface of the specimen is initially determined by shooting a single central ray to an object/interface. The beam model is then invoked to generate either a diverging beam or a cylindrical beam depending on the standoff distance. If a focused transducer is used then a focused beam is produced. Using the normal at the transducer face and a unit vector perpendicular to it, the direction of the rays originating from the transducer is found from vector algebra. The rays are created at the apparent origin and their origin is shifted along their direction of propagation to start from the face of the transducer. For cylindrical rays, the ray origin is shifted along this vector based on the distance required from the center of the transducer.

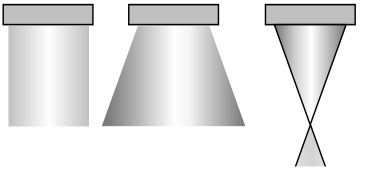


FIGURE 1. cylindrical, diverging and converging beams from a transducer.

BEAM MODEL

The amplitude distribution with which the rays are generated from a planar transducer is based on an approximate beam model derived from the exact single-frequency on-axis variation and the exact cross-axis distribution beyond the characteristic near-field to far-field transition distance a^2/λ corresponding to the wavelength (λ) at the specified central frequency and radius (a) of a circular transducer. Figure 2 depicts the on-axis variation, given by Equation (1), with three distance regions marked.

In Region I, the ray amplitude is taken to be independent of distance since for a pulse of finite bandwidth, the on-axis contributions due to all the frequency components average out. Further, the cross-axis distribution is taken to be uniform in Region I, constrained only by energy conservation, leading to a non-diverging cylindrical beam of diameter equal to that of the transducer. In Region III, the amplitude distribution follows an approximate Gaussian function that is matched to the exact expression involving the Bessel function given below

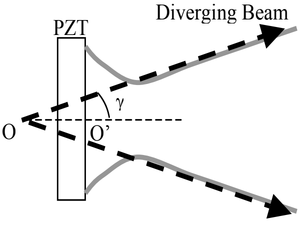
The Gaussian beam is currently matched to the 6 dB points of the exact cross-axis variation. Region II is a transition region and is modeled by a Gaussian distribution whose central maximum follows the exact on-axis variation with the cross-axis variation constrained by energy conservation. The distribution is matched with Region I and Region III distributions such that the exact on-axis variation is followed throughout. In Regions II and III, a single diverging beam is generated to approximate the main beam of a planar transducer.

The beam model for a spherically focused transducer is constructed in a similar manner based on the corresponding on-axis variation. The cross-axis variation at the focal plane is taken as the characteristic feature and an approximate Gaussian function is determined resulting in a single converging beam.

In the model, a divergent beam is generated from an apparent beam origin located behind the face of the transducer. Its location is determined from the near-field distance $(4a^2 - \lambda^2)/4\lambda$, and the half angle of divergence γ based on the 6 dB drop calculated from the well-know relation [6] $\sin\gamma = K_{6dB}\,(\lambda/a)$ where $K_{6dB} = 0.35$.

PROGRAM CAPABILITIES

The program provides an interactive display of the geometrical features of the object and of the transducer location and orientation. The user can locate and orient the transducer at any desired position with respect to the object. The user can also specify the scan path of the transducer relative to the object. The program allows for generation of simple canonical object shapes and provides for import of more complex object



$$OO' = \frac{4a^2 - \lambda^2}{4\lambda} - a\frac{\sqrt{4a^2 - K_{6dB}^2\lambda^2}}{K_{6dB}\lambda}$$

FIGURE 2. Representation of Beam Divergence - the 6 dB field contour (in grey) is modeled by the cone (in black dotted line) originating from an apparent origin O that is situated behind the transducer face centre O'.

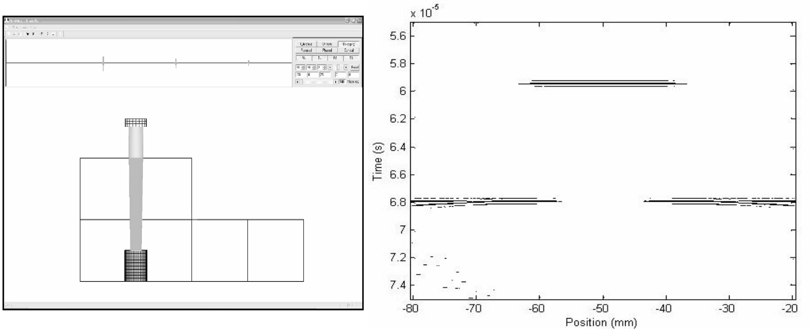


FIGURE 3. Snap shots of view panels corresponding to B-scan immersion mode of inspection over a FBH in a step block using a 0.5 in. dia, 5 MHz transducer under normal incidence. Panel on the left depicts the configuration and the instantaneous position of the transducer. The top section of this panel shows the A-scan. The right panel is a zoomed section of the B-scan over the FBH. The trace due to the backwall can be seen on either side of the trace due to the FBH.

geometries from standard packages such as AUTOCAD. The program can simultaneously display the inspection configuration and the corresponding A-scan. For a specified scan profile, a B-scan display can also be displayed. Currently, the program provides for conventional planar and spherically focused circular transducers and a linear phased array.

B-scan Simulation with Conventional Transducer

Figure 3 illustrates the B-scan feature where a circular planar immersion transducer was moved at a constant height above the sample. A standard calibration block 200 mm long with a step and a 20 mm diameter flat bottom hole (FBH) is considered in this example. The FBH is 25 mm in height and is centered at 50 mm from the end. The simulation was done using a ½-inch diameter, 5 MHz transducer. The beam spread was calculated to be 2º assuming a 6dB drop.

B-scan with Phased Array - Simulation and Validation

Linear phased array probes are modeled by combining rays from individual elements of the array with suitable time delay laws corresponding to beam steering and/or beam focusing. Figure 4 shows the simulated and experimental B-Scan of a 6mm notch in a 11mm thick plate. The scan was done using a 5 MHz transducer with a 45° beam steering. The experiment was carried out using OMNISCAN phased array module from RD Tech.

Pipe Inspection Simulation

SIMULTSONIC can internally generate simple shapes such as cylinders or pipes. Flaw detection and characterization even in such simple shapes depends very much on probe location and orientation and is controlled by the pipe dimensions and flaw orientation. Often, mode conversion can lead to complex signals that are difficult to interpret. Simulation is an economic alternative that can assist in identifying optimum probe positions and help interpret complex signals. Figure 5 shows the schematic of a 11 mm thick pipe of large radius of curvature with a 8 mm EDM notch of 1.5 mm

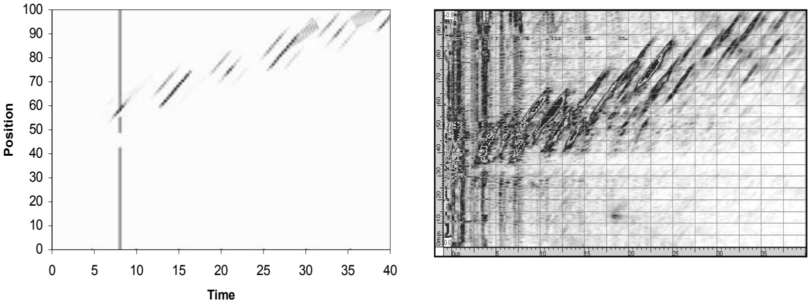


FIGURE 4. Simulated (left panel) and Experimental (right panel) Phased Array B-Scan of a 6 mm deep surface-breaking notch in a 11 mm thick plate. When superposed, the correspondence between simulation and experiment is very good.

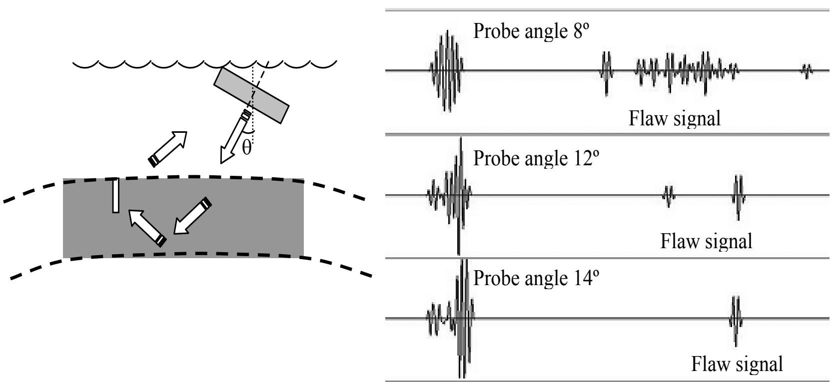


FIGURE 5. Simulation of the inspection, under immersion, of 8 mm long notch in a 11 mm thick pipe with a large radius of curvature. The transducer was taken to be 0.5 in. dia with 5 MHz centre frequency. The schematic of the configuration is shown on the left. Simulated A-scans for various probe angles are shown on the right. At a probe angle of 14° in water, a clear S-wave flaw signal can be seen.

width. The pipe is considered immersed in water and the material of the pipe is taken to be steel. The simulation is carried out on a region around the notch location approximated as a flat section due to the large curvature of the pipe. The EDM notch is modeled as surface opening cuboid.

The simulations were carried out for various probe angles. Mode converted signals can be seen for the probe angle at 8°. Probe angles of 12° or more appears to be well suited for detection of a vertical notch. As the first critical angle is at 13°, there is only one flaw signal for the probe angle of 14°, whereas there are two signals, one each from the shear and longitudinal waves for the probe angle of 12°.

THIN PIPE INSPECTION – SIMULATION AND VALIDATION

Optimization of the parameters for the inspection of a weld between two sections of a thin-walled pipe is the final example to be discussed in this paper. The pipe is a thin walled cylinder with a wall thickness of 0.4 mm and an outer diameter of 6.5 mm. Access is confined to be only in one section of the pipe with respect to the weld. Given the constraints of the problem, a 0.5 in dia, 15 MHz immersion transducer with a spherical focal length of 1.5 in, in water, was chosen for the task. An angle-beam inspection with shear waves was envisaged.

Simulations were carried out to find the optimum standoff distance as well as the optimum angle of inspection. The distance of the center of the probe from the wall to be welded was maintained as 1.5 in, to keep the wall in focus, and the probe angle was varied from 16º to 23º. Figure 6 shows the variation of the received energy with respect to transducer position as well as the transducer angle.

From the results obtained by simulations, the probe angle was chosen to be 19º, and the standoff distance was chosen to be 12 mm along the pipe axis with a corresponding vertical standoff distance of 35 mm.

An experiment was setup to validate the results experimentally. Figure 7 shows the pipe holder with supports, the XY-scanner, the probe in a manipulator and the immersion tank.

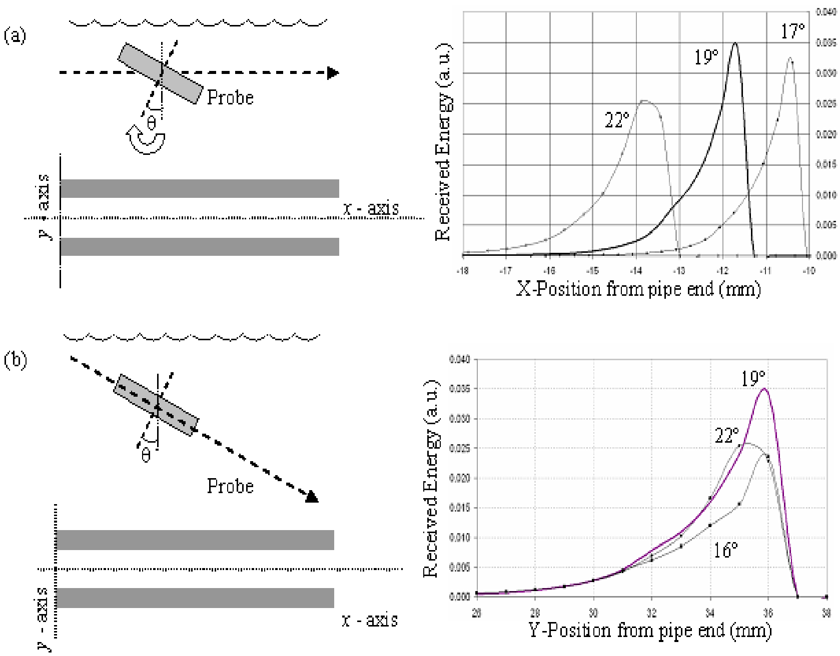


FIGURE 6. Simulation to determine optimum location and orientation of a focused probe. (a) Received energy as the probe was moved along the x-axis. The schematic is shown on the left. (b) The schematic on the left shows the probe scan path in the xy plane. On the right, the received energy as the probe was moved along the y-axis.

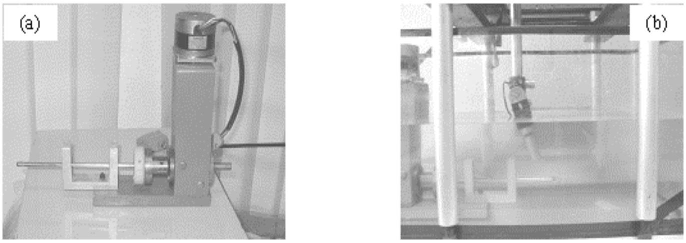


FIGURE 7. (a) Tube Holder with a Stepper Motor, (b) Probe manipulator mounted on a XY-scanner.

The pipe is mounted on two bushes to prevent wobble as it is rotated. A Lab-VIEW program was written to control the angular position of the tube, to control the probe fixed to the XY-scanner and for data acquisition. The probe manipulator was used to change the probe angle manually. The 15 MHz spherically focused transducer was powered by a Panametrics PR500 Pulser-Receiver. The signal was sampled at 100 MHz. Figure 8 shows the B-Scans obtained from the experiment and simulation.

The images show good correlation both with the arrival time of the signal as well as the amplitudes of the signals. It can be seen that as the position of the transducer is moved farther from the pipe wall the arrival time increases and the amplitude of the received signal also drops. It is also verified that the signal received is maximum at around 11-13 mm that was predicted during the initial studies. Figure 9 shows the sum of the peak-to-peak amplitudes obtained from simulation as well as experiments as a function of probe position.

The results obtained from experiments confirm the validity of the simulations.

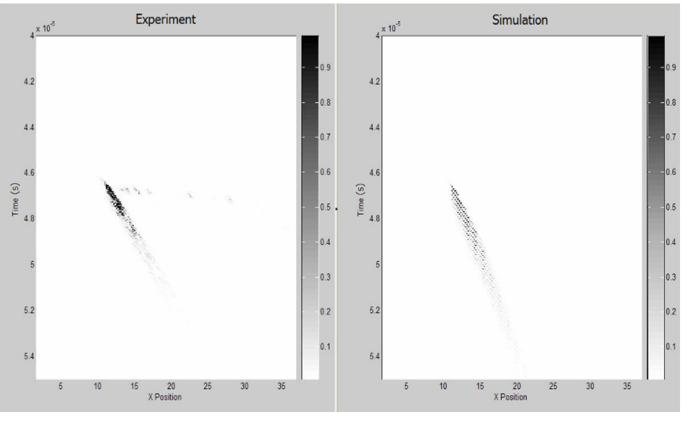


FIGURE 8. B-Scans obtained from Experiment (left panel) and Simulations (right panel)

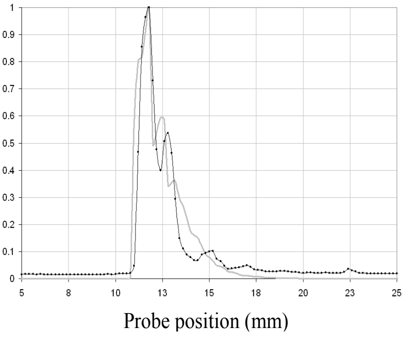


FIGURE 9. Measured (curve in black with dots) and Simulated (curve in grey) variation of the normalized received energy with probe position. The increase in amplitude at around 14 mm is noted both in experiments as well as in simulations.

SUMMARY AND CONCLUSIONS

SIMULTSONIC makes visualization of the insonified regions possible. Simple beam models provide a reasonable representation for circular planar and spherically focused transducers. A-scans and B-scans can be generated. SIMULTSONIC handles canonical geometries and supports import of surface meshes. The interactive GUI helps the user to specify/modify probe and object locations as well as to define probe scan paths. Delay laws for beam steering in linear phased arrays have been developed and validated with a phased array system. Simulations on thin pipes have been validated. On-going work includes providing a facility to import files made with graphic packages (e.g., ProE, UG) to represent components with complex geometries, incorporating GTD for crack response, and offering field calculations in specific cases.

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