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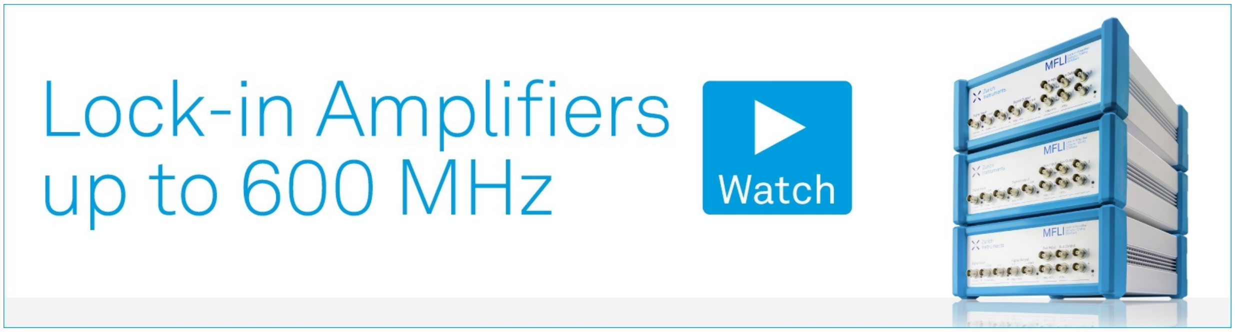

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A Study on the Prenatal Zone of Ultrasonic Guided Waves in Plates

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Abstract. Low frequency guided wave based inspection is an extensively used method for asset management with the advantage of wide area coverage from a single location at the cost of spatial resolution. With the advent of high frequency guided waves, short range inspections with high spatial resolution for monitoring corrosion under pipe supports and tank annular plates has gained widespread interest and acceptance. One of the major challenges in the application of high frequency guided waves in a short range inspection is to attain the desired modal displacements with respect to the application. In this paper, an investigation on the generation and formation of fundamental S_0 mode is carried out through numerical simulation and experiments to establish a prenatal zone for guided waves. The effect of frequency, thickness of the plate and frequency-thickness ($f*d$) is studied. The investigation reveals the existence of a rudimentary form with similar modal features to the fully developed mode. This study helps in the design and development of a high frequency guided wave generator for particular applications which demands waves with very less sensitivity to the surface and loading during the initial phase which immediately evolves to a more sensitive wave towards the surface on propagation for the detection of shallow defects.

INTRODUCTION

Guided wave based inspection is widely used in petrochemical and process industries to detect corrosion defects in structures [1-2]. The advantage of the method is that large areas can be inspected from a single location and the distance of propagation is a function of the frequency of transduction used. Recently High frequency guided waves were also applied for asset management, even though their spatial travel is limited due to their high frequency [3-6]. Using High frequency guided waves, short range inspections with high spatial resolution which would have been impossible with low frequency becomes possible and mapping of critical regions like annular plate of above ground storage tanks becomes easy. When we come to short range inspections it is really important to understand the behavior pattern of guided waves especially the formation zone, to design a transduction system which can effectively handle the dead zone for efficient inspection. In this work we are looking into the formation of guided wave in plates by focusing on the fundamental S_0 mode and the factors that govern this formation zone. Analytical simulations using DISPERSE [7] was used obtain the desired mode shape. Using FEM simulations, mode shapes at different cross sections were obtained and compared to the analytical mode shapes obtained through DISPERSE. The mode was deemed to be fully formed when the mode generated by FEM attains the analytically predicted mode shape.

The mode of generation chosen was an acrylic wedge based excitation to match with the mode of generation in high frequency guided waves so that a better understanding can be obtained [6]. Mild steel was chosen as the plate

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material since it is the most commonly used metal in target applications. Finite Element models were studied to find the dependence of frequency, thickness and the frequency thickness on the formation of guided waves. The model is validated with the help of an experiment using a differential laser Vibrometer. This paper is organized as follows. We begin with a description of numerical studies on fundamental S_0 mode in plates at different frequencies, thickness and frequency thickness. The experimental procedure for validating this result is then presented. FE results and trends validated by experiments are used to establish the fact that there is a possibility of a formation zone inside the plate in which the guided wave has a different mode shape than it's analytically predicted mode shape.

FINITE ELEMENT STUDIES

A 2D finite element analysis was conducted using the commercial package ABAQUS 6.11 to understand the underlying physics. A plate model was created with a dimension of 1000 mm x 6 mm. The plate was modeled to be excited by a wedge with an angle of excitation depending upon the frequency and thicknesses as obtained from DISPERSE [7]. The wedge dimensions and geometry were selected keeping in mind the ability to accommodate itself in the annular plate projection outside the tank, feasibility to attach itself to a moving crawler and to reduce the internal reflections. The model was meshed with 3 node linear plane strain triangle (CPE3) for the wedge and the plate with a 4 node bilinear plane strain quadrilateral (CPE4R) each of size 0.2 mm. The mechanical properties of PMMA, with modulus of elasticity E = 4.5 GPa, density ρ = 1180 kg/m^3, and Poisson ratio ν = 0.37 and the mechanical properties of mild steel with modulus of elasticity E = 200 GPa, density ρ = 7850 kg/m^3, and Poisson ratio ν = 0.33 were assigned to the wedge and the plate respectively. The wedge was excited by applying a time-varying force signal which is a 3 cycle Hanning windowed tone burst centered at the required excitation frequency. An iteration step time of 1e-9 s was used and the model was run for a total time of 170 µs. The propagation of the guided wave along the plate thickness was then simulated in a 2D plane strain configuration. The waves were monitored at cross sections starting from the tip of the wedge which are 50 mm apart in order to identify the displacement profiles generated at each cross section. Once the desired profile is obtained that sub section is further divided into segments 5 mm apart to determine the prenatal zone.

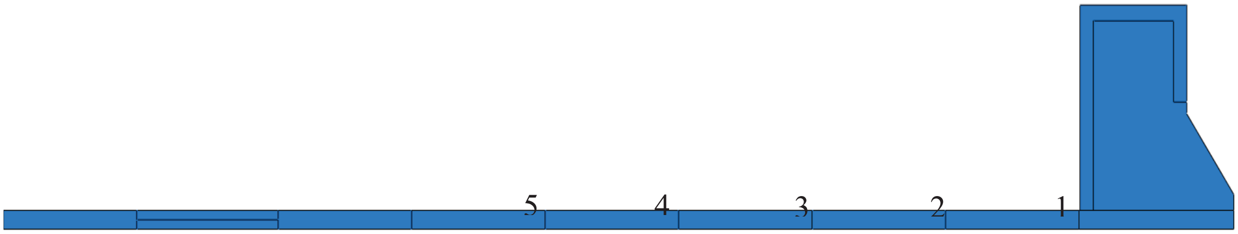

FIGURE 1. 2D model of the problem developed in ABAQUS CAE

In order to obtain the displacement profiles across the thicknesses, time traces of both the in-plane and the out-of plane components were collected across all the nodes at various cross sections of interest. At each cross section, the time corresponding to the maximum of absolute value of Hilbert transform of all recorded time traces across the cross section was taken as the reference time 'T'. The displacement component values of all nodes in a particular cross-section were measured at this time 'T' and were plotted as a function of the plate thickness against nodes to obtain the instantaneous displacement pattern. To understand the effect of frequency 3 deferent frequencies 100, 200 and 300 kHz were used on a 6 mm plate. To understand the effect of thickness a 100 kHz frequency was excited over 6,9,12 and 15 mm. To understand the effect of frequency thickness an f*d of 1.2 was selected which was held constant with varying frequencies and thickness.

EXPERIMENTAL METHODOLOGY

Experiments were carried out on the mild steel plate with dimensions 500 mm x 500 mm x 6 mm. The photograph of the experimental setup including the plate specimen is shown in the figure. A custom wedge made from PMMA with a 300 kHz crystal bonded to it damped for better sensitivity and to reduce internal reflections was used for wave generation, which was driven by a RITEC RPR 4000 pulser-receiver that generates a 3-cycle tone burst signal. The signals were monitored using the laser Vibrometer with dual differential fiber optic lines (Polytec OFV 552). A thin reflective film was attached to the plate to enhance the optical backscattering of the laser beam. The two laser beams aligned at an angle of 60 degrees were focused on the same spot, thus the difference between these two signals gives the amplitude of the out of plane displacement.

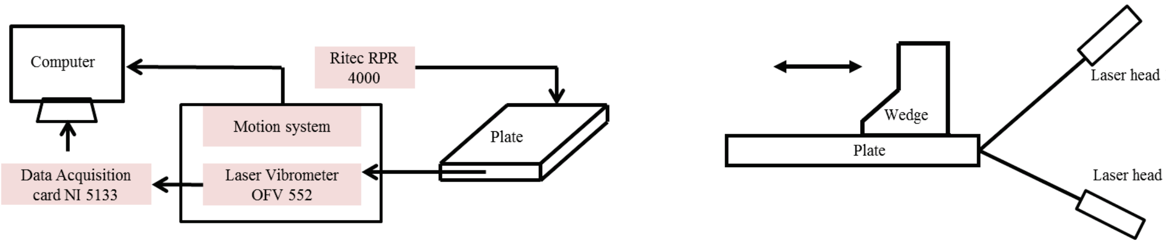

FIGURE 2. Schematic of experimental setup

The output from the laser controller was sent to a digital USB controlled data acquisition card (National Instruments 5133), which operates at a sampling rate of 100 MHz. The data acquisition card is connected to a computer interfaced with a motion controller which moves the laser heads along the thickness of the plate collecting data at every 0.2 mm. The manipulator uses a ball screw linear motion guide setup which is stepper motor driven and employs a closed loop control system using feedback from encoders to ensure precise and accurate movement. A custom made software communicating with the motion system and data acquisition system simultaneously was used to record the A scans along the through thickness automatically at fixed intervals.

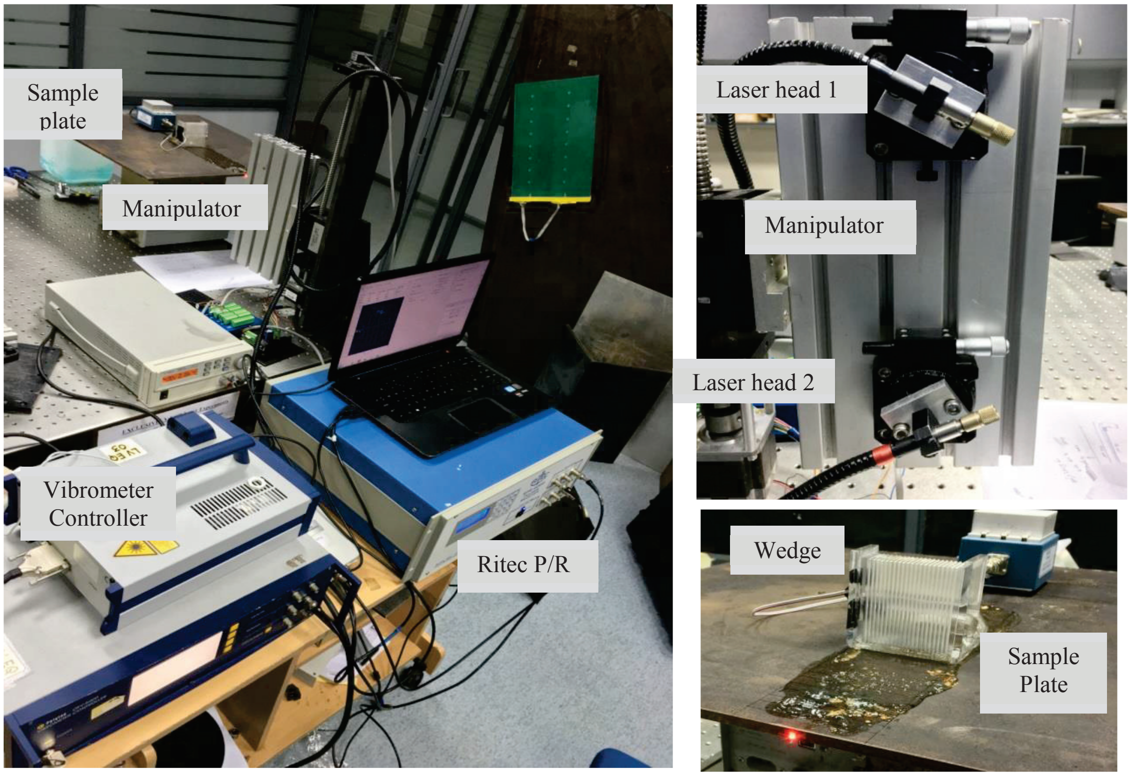

FIGURE 3. Photograph of the experimental set up

The wedge was kept close to the plate edge and data was recorded across the thickness of the plate. The next set of data was recorded by moving the wedge 10 mm away from the plate edge which was repeated .By following this procedure mode shapes at different stages of wave propagation can easily be calculated from the data recorded.

RESULTS

Finite Element Simulations

The figure below shows the mode shapes before formation and after formation when a 6 mm plate is excited with a 100 kHz wedge at an angle of excitation of 31 degrees. The mode shape obtained at formation from the FEM studies is similar to the analytical mode shape predicted by DISPERSE.

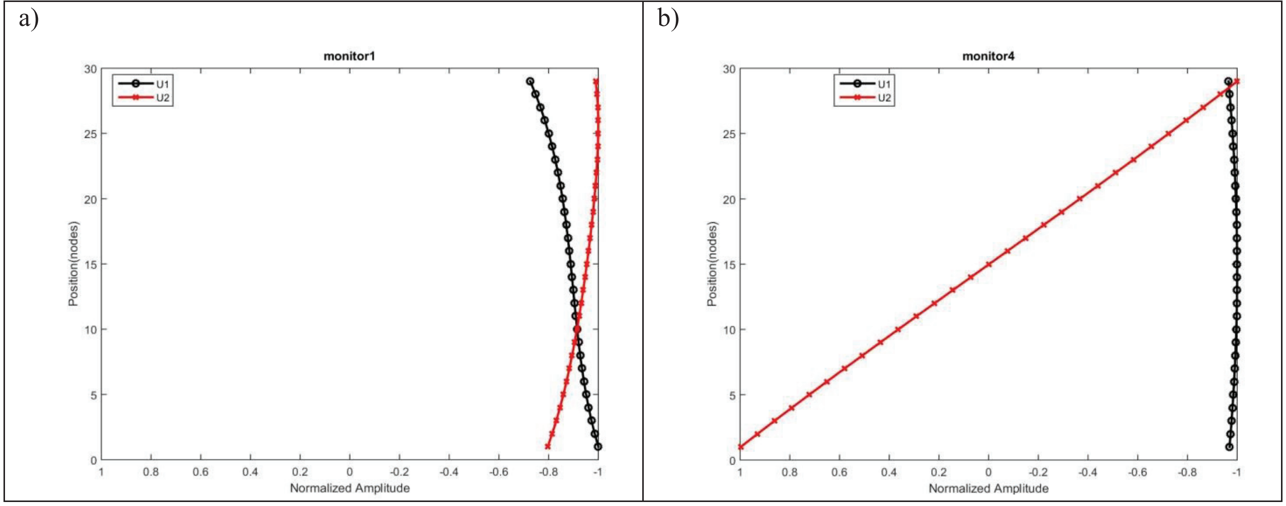

FIGURE 4. Normalized in-plane (black) and out-of-plane (red) displacements of wave propagation inside the plate a) before formation b) After formation

Here the distance of formation where a matching mode shape emerged was at 206 mm. Similarly the formation distances for other models were also found out which were matching with the mode shapes obtained from disperse and the trends are plotted as shown below

FIGURE 5. The graph shows the effect of frequency on guided wave formation in a 6 mm plate when the frequency is increased from 100 to 200 and 200 to 300 kHz . It is seen that the as the frequency is increased formation zone inside the material decreases

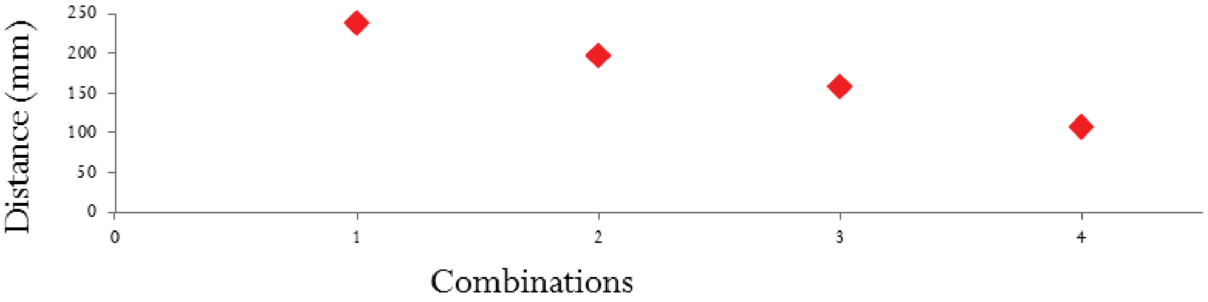

FIGURE 6. The graph shows the effect of frequency thickness where f*d is held constant at 1.2 MHz-mm and the combinations are varied. The graph is plotted for the combinations 0.08*15, 0.1*12, 0.133*9 and 0.2*6 (MHz*mm). Higher the frequency and lower the thickness faster is the formation.

Experimental Results

The figure below shows the mode shapes obtained from experiment before formation and near to formation inside the plate. The mode shape near to formation is similar to the mode shape obtained from FEM.

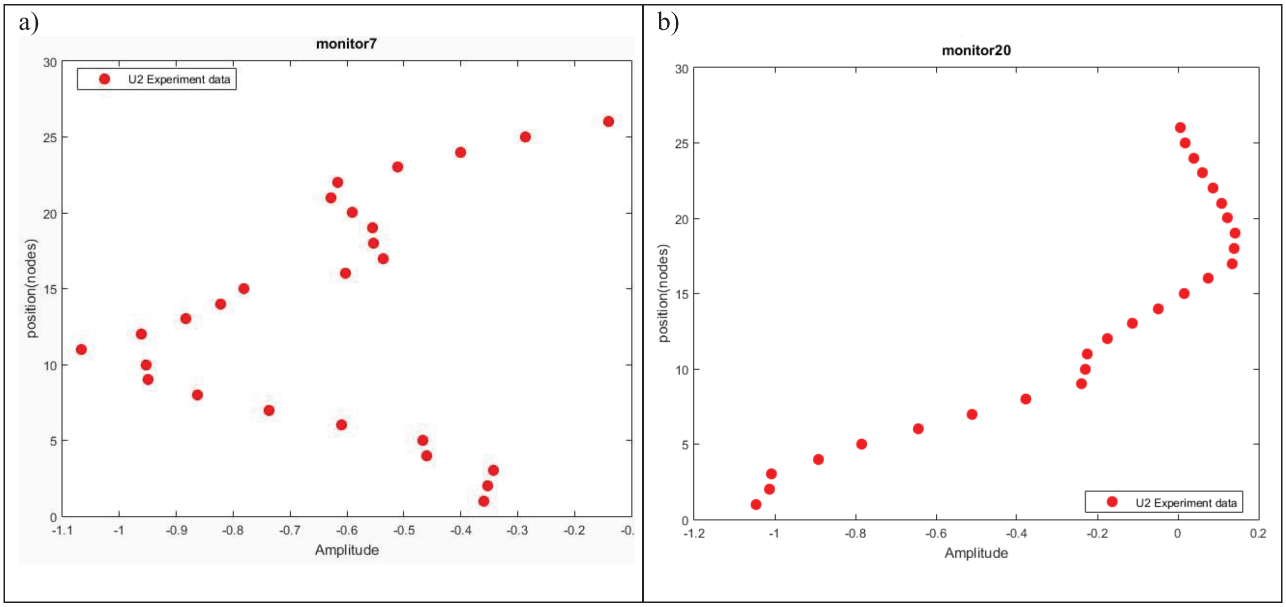

FIGURE 7. Out-of-plane displacement mode shapes obtained experimentally a) before formation b) at near formation.

DISCUSSION

Finite element studies carried out on different models shows that there is a pre formation zone where the waves when sent inside the material undergo interference to form the pure mode shapes of the excited mode. In this paper the mode shape of the fundamental S_0 mode is obtained from DISPERSE based on the different excitation parameters and is compared with the mode shapes obtained from FEM. The theoretical mode shape is only obtained after a certain distance of traverse inside the wave guide and this distance varies as a function of frequency. The effect of thickness is negligible in a the range studied but as the thickness crosses the range the formation range also increases as expected due to lesser interaction with boundaries for larger thicknesses. Even for a constant frequency-thickness the formation zone is not constant, higher the frequency and lower the thickness faster is the formation. For a 100 kHz frequency the distance of formation is 206 mm which means when we are going to frequencies of much higher order like 2 MHz the formation zone is going to be negligible and should not affect the near field inspections.

Experimental validation was carried out using a differential laser Vibrometer on a 6 mm plate excited with a 300 kHz probe at an angle of excitation of 31 degrees. The out-of-plane mode shapes were recorded at an interval of every 10 mm and the results show that at 170 mm the waveforms starts stabilizing and from 170 to 200 mm the waveforms collected shows a similar shape which indicates that the mode is in a near formation zone. A reflective tape was used to get better laser response from the surface which had some form limitations. The reflective area was limited to the form of a hexagon which didn't cover the entire thickness due to which after measuring some points we had to relocate the tape. This is assumed to have caused some error in the measurements but still an approximate match with the theoretical out-of-plane mode shape was obtained. The in-plane mode shapes were not recorded since it mostly followed a flat line curve and didn't show much change for different frequency-thickness ranges. In High frequency guided wave simulations it was found that the out-of-plane displacements were significantly larger than that of the in-plane displacements which made us limit the study to only out-of-plane displacements.

CONCLUSION

The work presents the possibility of a pre formation zone for guided waves in plates before they evolve into a fully formed wave based on the criteria of mode shape. FEM studies and experiments were carried out to demonstrate the phenomenon and it is found that a pre formation zone exists and this zone is a function of the frequency of excitation. Higher the frequency of excitation faster is the formation and smaller is the formation zone. At a constant frequency thickness larger the frequency and smaller the thickness faster is the formation.

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