ULTRASONIC WAVE PROPAGATION THROUGH SOLID MEDIA

A Dissertation submitted

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MASTER OF ENGINEERING
in
CAD/CAM ENGINEERING

Submitted by

Vishal Dhiman

Roll No. 801481025

Under the Guidance of

Dr. Sandeep Kumar Sharma

Assistant Professor,

Mechanical Engineering Department,

Thapar University, Patiala

DEPARTMENT OF MECHANICAL ENGINEERING

THAPAR UNIVERSITY, PATIALA

July, 2016

CERTIFICATE

I hereby declare that thesis entitled "**ULTRASONIC WAVE PROPAGATION THROUGH SOLID MEDIA**" is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering** in **CAD/CAM** Engineering at **Thapar University, Patiala** under the supervision of **Dr. Sandeep Kumar Sharma**, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala during July 2014 to July 2016. No part of the matter embodied in this report has been submitted to any other university or institute for the award of degree.

Date: 15/July/2016

Vishal Dhiman

It is certified that the above statement made by the student is correct and best of my knowledge and belief.

Dr. Sandeep Kumar Sharma

Mechanical Engineering Department

Thapar University, Patiala-147004

Countersigned by

Dr. S.K. Mohapatra

Head, Mechanical Engineering Department

Thapar University, Patiala-147004

Dr. S.S. Bhatia

Dean of Academic Affairs

Thapar University, Patiala-147004

Dedicated to

My grandparents

Lt. Sh Chajju Ram Dhiman

&

Smt. Giano Devi

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Abstract

Structural health monitoring is an emerging technology which is used broadly to identify, locate, and quantify structural flaws or damages before failure. Ultrasonic guided waves are used to detect the defects in the structures in dry conditions or immersed in liquid without causing any effect to it. Lamb waves are widely used as they can travel large areas. With the development of various simulation techniques, it is interesting to see whether wave modeled in these simulation tools can exhibit integral characteristics of the lamb wave. The objective of this research is to determine the responses of Lamb wave generated using finite-element software package ANSYS and asses its propagation in an isotropic healthy plate. Further the FE model is used to investigate the interaction of Lamb waves when the subject plate is subjected to different environment i.e. plate in air, plate immersed in liquid. Artificial defects like notches are generated to check the fidelity of the model in detecting flaws. Propagation characteristics of different Lamb wave modes are studied in the plate specimen and experimental results are also generated to validate the model.

Key words: Ultrasonic Guided waves, Structural health monitoring, ANSYS, Lamb waves, defect detection, mode sensitivity

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Abbreviations and Symbols used

DOF	Degree of freedom
D_p	Propagation distance
FEM	Finite element method
NDE	Non-destructive evaluation
SHM	Structural health monitoring
DPSM	Distributed point source method
SEM	Spectral element method
BEM	Boundary element method
λ	Wave length
α	Integration parameters
β	Integration parameters
2D	Two Dimensional
V_{gr}	Group velocity
V_{ph}	Phase velocity
Δt	Time step

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Chapter 1
Introduction

1.1 Background and Motivation

Damage detection has been main area of concern in the design and maintenance of various military, civil and industrial structures and other equipments exposed to humid and non-humid environments. There are several areas where mild steel in the form of plates has been vastly used. With change in time there are several degradation factors like environmental conditions, fatigue, corrosion etc which also affects the durability of the structure. In some of conditions (submerged in water) it is very difficult to inspect the condition of the structure. If these deteriorations remain unobserved then it may lead to failures and huge loss to human race, monetarily and physically also. There is a need to develop a reliable, non-invasive and in-situ technique to avoid this catastrophe.

In ultrasonic non-destructing testing high frequency (greater than 20kHz) are propagated into the object to find the defects in the objects without altering or damaging the material properties. Ultrasonic waves are simply organized sound waves travelling through a medium[2]. These waves travels through a given medium at a specific velocity, in a known direction. Literature has established that in the past this technique has been broadly used in the detection of damage in plate structures. With the development of simulation tools like ANSYS, ABAQUS CAE, COMSOL, LS-DYNA etc several models are developed in these environment and results are validated with theoretical and experimental results. But still very less work has been done in the area of immersed bodies. So in the present work a plate immersed in water has been modelled in ANSYS. A study has been carried out regarding the behavior of the wave with the presence of defects in the structure. Experimental work has also been carried out to validate the model.

1.2 Existing Non Destructive Testing Techniques

The aim of all NDT techniques is to detect defects in the materials without causing any affect to the material properties. There are various techniques which are used to test and inspection of the defected objects.

1. Visual and optical testing (VT)
2. Radiographic testing (RT)
3. Electromagnetic testing (ET)
4. Ultrasonic testing (UT)
5. Liquid penetrant testing (PT)
6. Magnetic particle testing (MT)
7. Acoustic emission testing (AE)

1.2.1 Visual and Optical Testing (VT)

This is the most widely used technique and the oldest of all NDT technique. Although it is not possible to quantify the observation made, it is very important that all inspection include preliminary visual check during which abnormal conditions such as high wear, corrosion, erosion, impact damage, distortion, discoloration, missing parts etc. can be noted. Based on these findings, the course of further inspection is generally decided.

1.2.2 Radiography Testing (RT)

Radiography is NDT method based on the principle of differential absorption of penetrating radiation by object under test. Owing to the varying characteristics or composition of the structure of the test object, different portions absorb different amounts of penetrating radiation. The radiation passing through without being absorbed is recorded on a film and viewed on an illuminated screen. The picture thus seen is used to locate defects in the test object. Literature cites the potential of radiographs to detect flaws in casting, forging, and welds in metals. Various discontinuities like pores, cracks, holes etc can be traced using radiographic techniques. Despite safety and expensiveness of this technique it is broadly used even now a days also.

1.2.3 Ultrasonic Testing (UT)

In this inspection technique, high frequency sound waves are sent into the object under test. The sound wave travels through the material as shown in Fig. 1.3**.** There is a decrease in the energy with increase in propagation span and also at interfaces. A receiver probe collects the reflected signal, which is further analysed to detect location of defect in the object under inspection. Law of optics is followed by the wave while propagating. This technique is broadly applied to measure the thickness and detection of flaws in the material or object etc. In the recent time emphasis has been given to develop phased array ultrasonic testing. Pulse echo technique is broadly used for inspection, in pulse echo a sound wave is emitted into the testing object and reflections (echoes) are received in the receiver from internal flaws or other side of the testing object. These testing can be used for detecting various surface as well as internal defects.

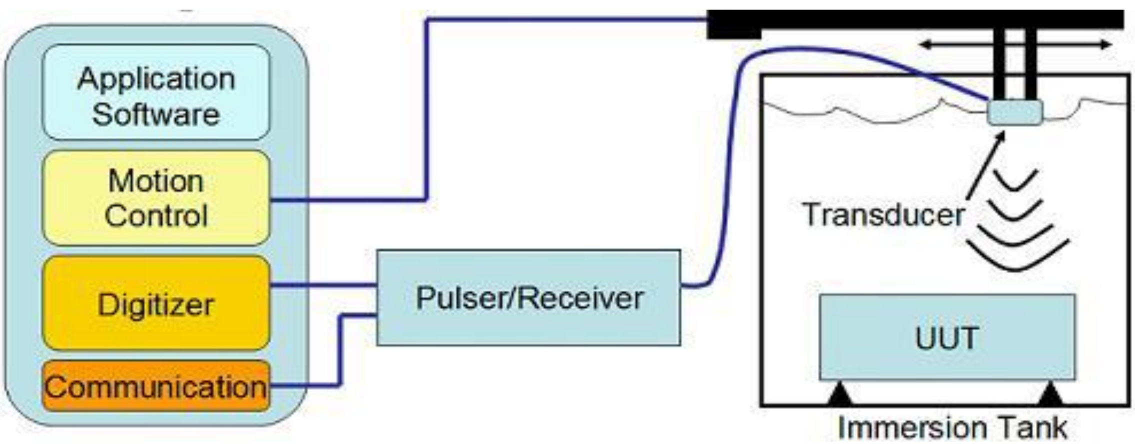

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Figure 1.1 Ultrasonic testing Method [3].

1.2.4 Penetrant Testing (PT)

This is an aided visual technique. In this method a bright coloured liquid which penetrates into cracks and fissures open to surface is used. First the surface is thoroughly cleaned and wiped clean. A penetrant is sprayed onto the surface. The bright coloured penetrant seeps into all surface flaws. The surface is now carefully wiped clean to remove all the excess dye on the surface. A developer is applied to the surface. White coloured developer has a blotting action on the dye and draws it up to the surface. A bright coloured indication of the flaw is presented to the inspector.

1.2.5 Techniques of Ultrasonic Testing

When ultrasonic energy hit the interface of two unlike materials either it strikes at normal angle or at any inclined angle, the energy is partially reflected or partially transmitted into the next medium. Transmitted energy is used in inspection work. There are various techniques available which are applied based on the conditions and kind of information required.

Various techniques of ultrasonic most commonly used are:

- Pulse echo method
- Through transmission method
- Pitch- Catch Method

1.2.6 Pulse Echo Method

In this method, a PZT transducer with its longitudinal axis normal is mounted on the surface of the material to be tested. Same transducer is used to transmit and receive UGW. Energy transmitted into the material is reflected back to the transducer either by the other face or by the flaws if any present in the material. Received signal is further processed and displayed on the video monitor as shown in the Fig. 1.2. Various attributes of the material like depth of the material, location of the defect (if any) can be generated with proper knowledge and availability of hardware and software.

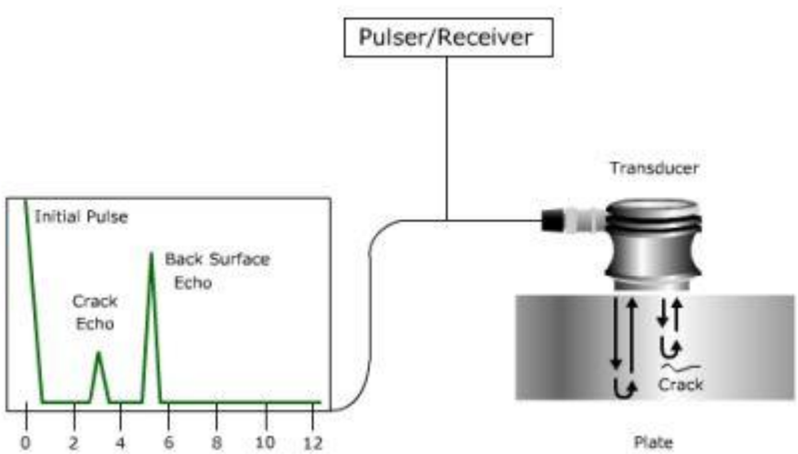

Figure 1.2: Pulse Echo Method [3].

1.2.7 Through Transmission Method

In this method two transducers are used for inspection of the specimen. Both the transducers are placed on the either side of the specimen. Here, one transducer acts as pulse generator whereas the other one is pulse receiver Fig.1.3. Pulse echo is mostly used to detect and localise the defect, whereas pulse transmission is used for sizing of the defect. There is a drop in the signal amplitude with the presence of defect in the specimen. So, by comparing the relative alteration in the signal i.e. input and output signal, severity of defect can be analysed.

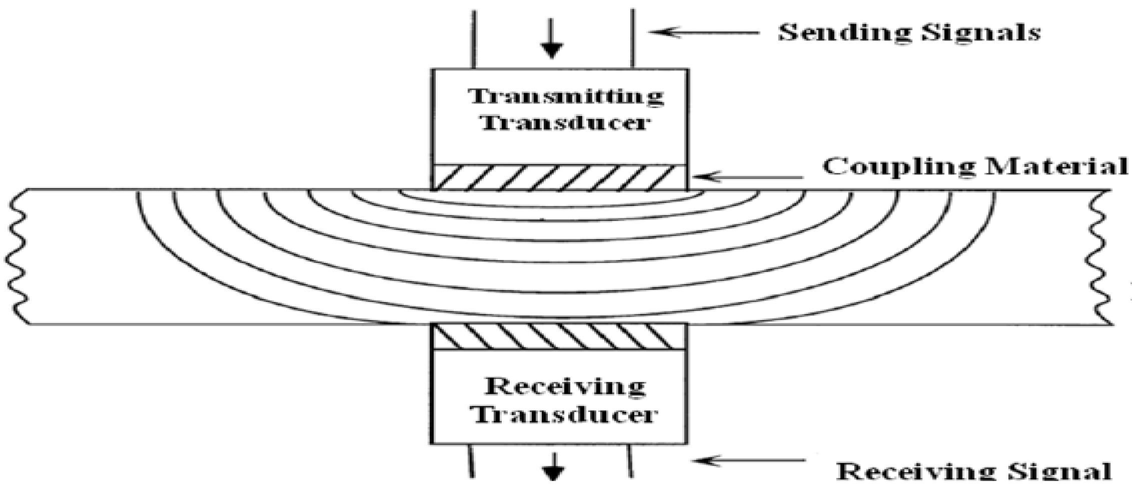

Figure 1.3: Through Transmission Method [4].

1.2.8 Pitch Catch Method

The pulse echo method can be used with either single or double crystal unit in single transducer unit the probe acts as both transmitter and receiver. In two transducer arrangement, one transmits and other receives the ultrasonic waves. These are placed on same side of specimen. Pulse wave is send into the specimen by the transducer (T) and the echoes reflected from the back surface or any defect are received by the transducer (R) and displayed on the flaw detector screen. For specific applications like wall thickness measurement special type of transducers in which the transmitting and the receiving crystals are housed in a single unit are also used.

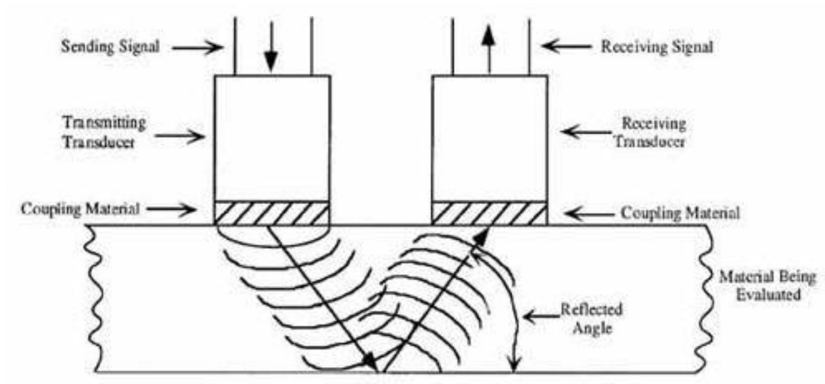

Figure 1.4: Pitch Catch Method [4].

1.3 Aims and Objectives

The aim of the present work is to model a lamb wave in the plate in FEM based simulation tool ANSYS. The developed model should show characteristics features of lamb wave. Lamb wave in a plate in dry state will be modelled first and then key characteristics of the wave will be validate with theoretical and experimental results. Further a plate immersed in liquid will be modelled. So the objective are as follows:

- Investigation of lamb wave characteristics in dry plate modelled in ANSYS
- Investigation of propagation characteristics lamb wave through healthy and damaged plate submerged in liquid modelled in ANSYS
- Determination of sensitivity of waves to typical damages
- Validation of modelled results with experimental results.

1.4 Layout of Thesis

The thesis work carried out is organised in the following chapters:

In the **First Chapter,** importance of the UGW techniques is highlighted and also the objective of the research work is stated. In this chapter various NDT technique are also specified.

Chapter two specifies various modes of wave propagation, different categories of sound wave etc. Basic terminologies used in wave propagation are also briefly explained in this chapter. Characteristic behaviour of lamb wave is also explained.

Chapter 3 illustrates various method which are used to model wave numerically. In this chapter pro and cons, applications of various method is highlighted.

Chapter 4 present the literature review of latest work done till date using lamb waves for damage detection in the plate structures and also compiles application FEM in the study

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In **Chapter 5** ultrasonic lamb wave is modelled in dry plate with FE based tool ANSYS**.** Characteristics of the wave generated are verified with theoretical and experimental results.

In **Chapter 6** lamb wave is further modelled in plate structure submerged in water using ANSYS. Mode sensitivity of the modelled wave is studied to check the fidelity of the ANSYS model created. Results are further verified with experimental studies.

Chapter 7 summarises the present work and conclusions derived from the studies are reported.

Chapter 2

Wave Propagation in Plate structures

2.1 General

Ultrasonic waves are used to detect location and magnitude of defects in the material. This is the best technology or technique for inspection of the material as this technique doesn't affect any property of material. This technique is used to inspect metals, ceramics and plastics materials. There is variation in the characteristics of wave with change in the medium.

2.2 Wave Propagation through Solids

The ultrasonic waves propagate in a number of ways in a medium. Wave propagation depends on material properties of the structure. Taking mode of particle displacement into consideration, waves are further categorized as:

1) Longitudinal or Compressional waves (L-waves).

2) Transverse or Shear waves (S-waves)

3) Surface or Rayleigh waves.

4) Lamb or Plate waves

2.2.1 Longitudinal or Compressional Waves

These waves are also called compression waves. In this type of ultrasonic wave alternate compression and rarefaction zones are produced by the vibration of the particle parallel to the direction of propagation of the wave. Particles oscillate in the direction of propagation. The particle density fluctuates with propagation due to which wave is also called 20 density wave. These waves can propagate in liquid as well as gaseous medium as the energy moves through atomic structure following compression and expansion movements.

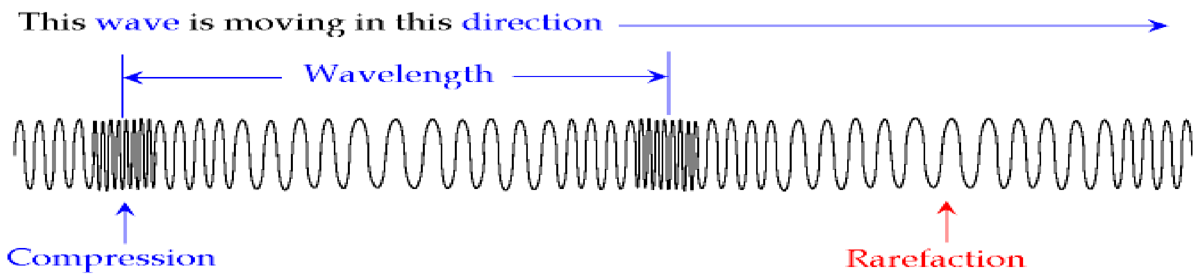


Figure 2.1: Propagation of Longitudinal Waves [2].

2.2.2 Transverse or Shear Wave

When the particles oscillate perpendicular or transverse to the direction of wave propagation, it is called Transverse or Shear wave. These waves propagate effectively in solid medium, and very less effectively in liquid or gaseous medium. For such a wave to travel through a material, it is necessary that each particle of material is strongly bonded to its neighbours so that, as one particle moves it pulls its neighbour with it, thus causing the ultrasound energy to propagate through the material. As compared to longitudinal waves shear wave relatively weaker. Velocity is 50% less than that of the longitudinal waves. Only viscous liquid or very thin layer of liquid can support the propagation of transverse wave, as in loosely bonded material like air and liquid it does not propagate.

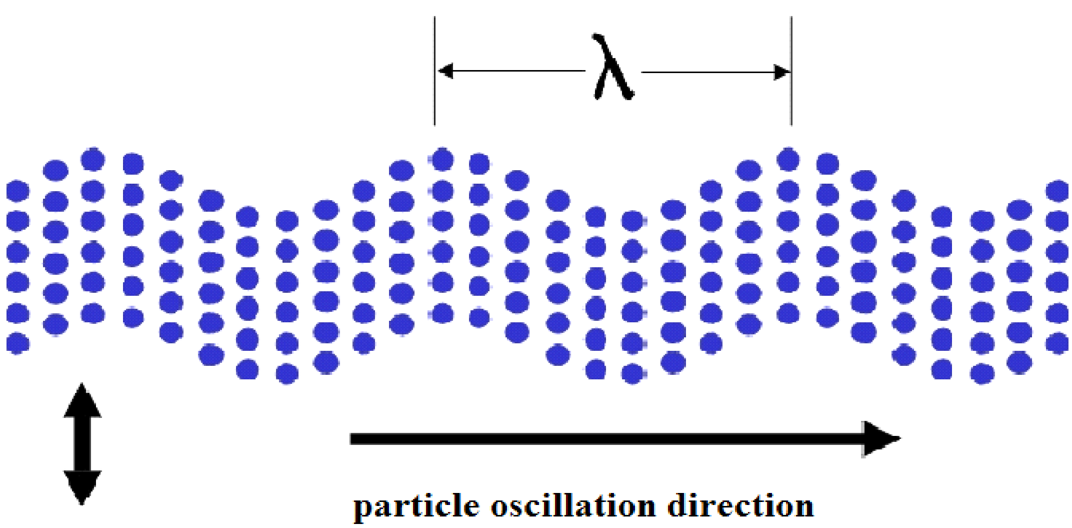


Fig.2.2: Propagation of Transverse Waves [5].

2.2.3 Surface (or Rayleigh) Waves

Surface (or Rayleigh) waves propagate on the surface of thick solid material and penetrate up to depth of one wavelength. These wave only propagates liquid if the surface of solid is immersed in very thin layer of fluid. In surface waves particle vibrations generally follow an elliptical path. The major axis and minor axis are normal and parallel to surface along which the waves are propagating. These waves are very sensitive to surface defects, as particles of the wave follows surface around curves. These waves can travel along the flat and curved surfaces. These waves are less attenuative as compared to transverse and shear wave in given material, which enhances its application in various areas where other waves cannot propagate.

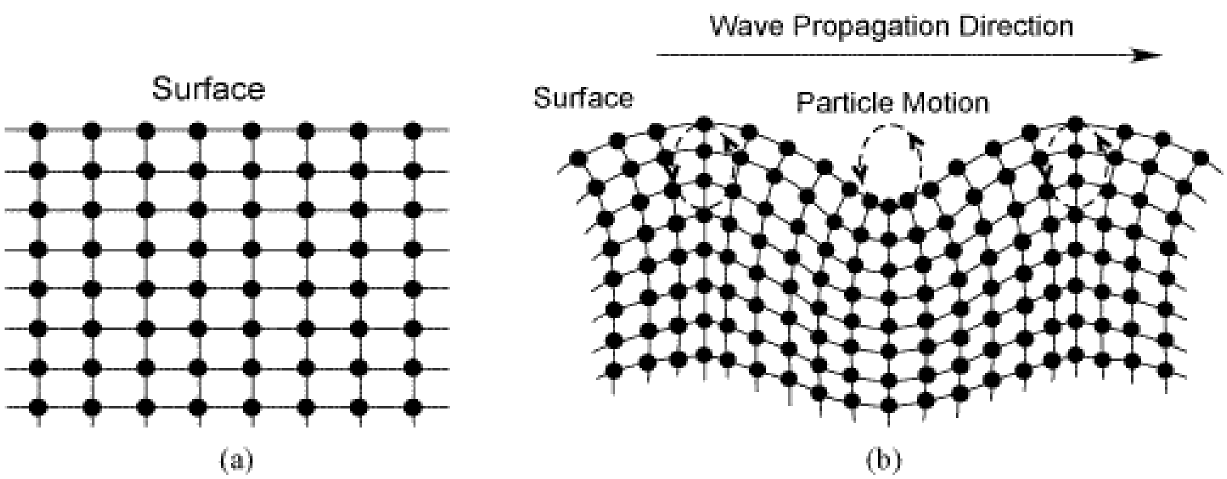
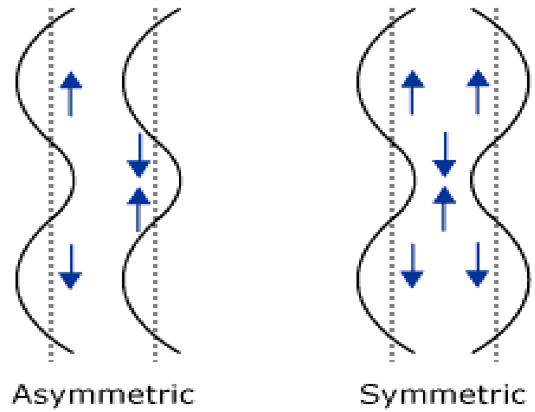


Figure 2.3: Propagation of Surface waves [4].

2.2.4 Lamb Waves

When the waves are propagating through a plate like structure it is called lamb waves. These waves are named after Hoarse Lamb. These waves are mostly used to detect flaws in plate like structures. Factors which affect the propagation of the lamb wave are density (ρ), modulus of elasticity of material, thickness of the structure and frequency at which wave is generated. There are two main wave modes generated in lamb wave symmetric(S) and anti-symmetric (A). In Symmetric wave mode wave particles moves in symmetric fashion along the median of the plane, whereas in Anti-symmetric mode wave particles oscillates in anti-symmetric fashion.

Symmetric modes are also known as ‘stretching and compressing’ as shown in Fig. 2.4. Anti-symmetric modes are also popular as “Flexural mode” as largely the wave motion is normal to the surface of plate.



(a). (b).

Figure 2.4: Lamb wave propagation (a). Asymmetric (b). Symmetric [5].

2.3 Terms used in Wave Propagation

2.3.1 Attenuation of Waves

The intensity of sound wave depreciates with increase in distance. It is due to spreading of the sound amplitude or pressure. But in addition to that there are other factors which reduce the intensity of the signal i.e. scattering and absorption. The deviation of sound wave from its original path is called scattering, whereas absorption is the conversion of one form of energy to another. The cumulative effect of both these factors is called attenuation. Attenuation is proportional to square of sound frequency.

The amplitude change of a decaying plane wave can be expressed as:

$$A=A0e\text{-}\alpha Z$$

...(1.1)

where;

A0: initial (un-attenuated) amplitude

α: attenuation coefficient (Np/m)

Z: travelled distance (m)

2.3.2 Refraction and Snell's Law

When a wave propagates through an interface between two different materials at some angle, at if the material has different refraction indices then both reflection and refraction will take place. Same phenomenon is applicable to light also. Figure 2.6 shows that when a wave propagating through a material enters others which exhibits higher acoustic velocity, at interface portion of the wave in the material with high acoustic value start to travel faster than the other potion of the wave still in the other medium leading to bending and change in direction of wave, known as refraction.

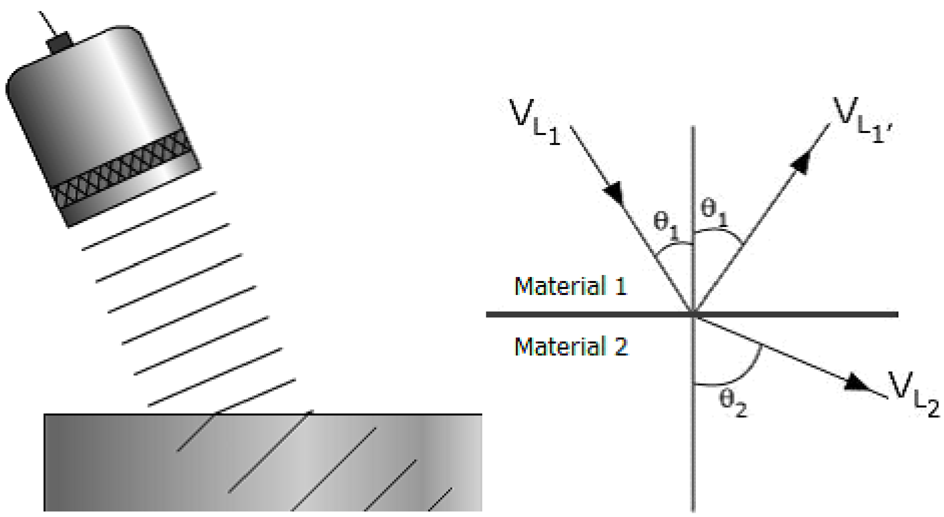


Figure 2.5: Shows a wave passes through interface [6].

Snell's Law describes the relationship between the angles and the velocities of the waves. Snell's law equates the ratio of material velocities to the ratio of the sines of incident and refracted angles, as shown in the following equation:

$$\frac{Sin\ \theta\ 1}{VL1} = \frac{Sin\ \theta 2}{VL2} \qquad \text{…..(2)}$$

Where,

VL1and VL2: the longitudinal wave velocities in the first and second materials.

θ_1 andθ_2: the angles of incident and refracted waves

As shown in the diagram, the reflected longitudinal wave is reflected at the same angle as incident as both the waves are travelling in the same material, hence exhibits same velocities. This reflected wave is neglected as per Snell’s law, still some energy is reflected at the interface.

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2.3.3 Mode Conversion

When sound travels in a solid material, one form of wave energy can be transformed into another form. For example, when a longitudinal wave strikes an interface at an angle, partial energy of wave can cause particle movement in the normal direction to excite a shear wave. Mode conversion occurs when a wave faces an interface among materials of distinct acoustic impedances and the incident angle is not perpendicular to the interface Mode conversion take place every time wave experience an interface. Mode conversion took place in both the portions of wave i.e. refracted and reflected wave. Snell's Law holds true for shear waves as well as longitudinal waves and can be written as follows:

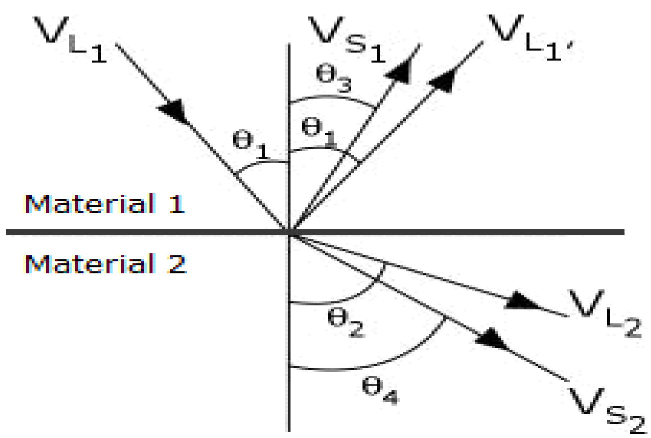


Figure 2.6: Snell’s Law [5].

$$\frac{\sin\theta 1}{VL1} = \frac{\sin\theta 2}{VL2} = \frac{\sin\theta 3}{VS1} = \frac{\sin\theta 4}{VS2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where:

VLI AND VL2 : the longitudinal wave velocities in the first and second materials.

VS1 and VS2 : the shear wave velocities in the first and second materials.

θ1 and θ2: the angles of incident and refracted waves.

θ3 and θ4: the angles of converted reflected and refracted waves.

2.3.4 Acoustic Impedance

Sound wave travels through a medium under the effect of sound pressure. In solid material molecules are bonded together very tightly, it is the excess pressure of the sound that results propagation of wave in a solid medium. Acoustic impedance (Z) is the product of density (ρ) and acoustic velocity(v) of the material.

$$Z= pv \qquad \ldots (2.1)$$

Acoustic impedance is used to determine acoustic transmission of reflection at the interface.

2.4 Dispersion and Its Effects

Although using Lamb waves is quicker and effective means of health monitoring as compared to bulk waves, but they are very difficult to interpret. So it is very important to highlight and understand some of the characteristics of the Lamb waves to use as a health monitoring tool. Dispersion is key characteristics of lamb waves. The phenomenon of wave speed dependence on frequency and thickness is called dispersion. Due to dispersion different wave modes are generated at same frequency. Dispersion curves of a 10 mm thick plate is shown in the figure 2.7. Symmetric and anti-symmetric waves are shown in red and blue respectively. The graph shows a relation between group velocity and frequency and Phase velocity and frequency.

- Red lines represents symmetric waves.
- Blue lines represents anti symmetric waves.

We can conclude from the graphs that symmetric waves are much faster than anti symmetric waves. And also with increase in frequency the number of modes also increases and it is very difficult to settle differentiate and choose the appropriate wave mode.

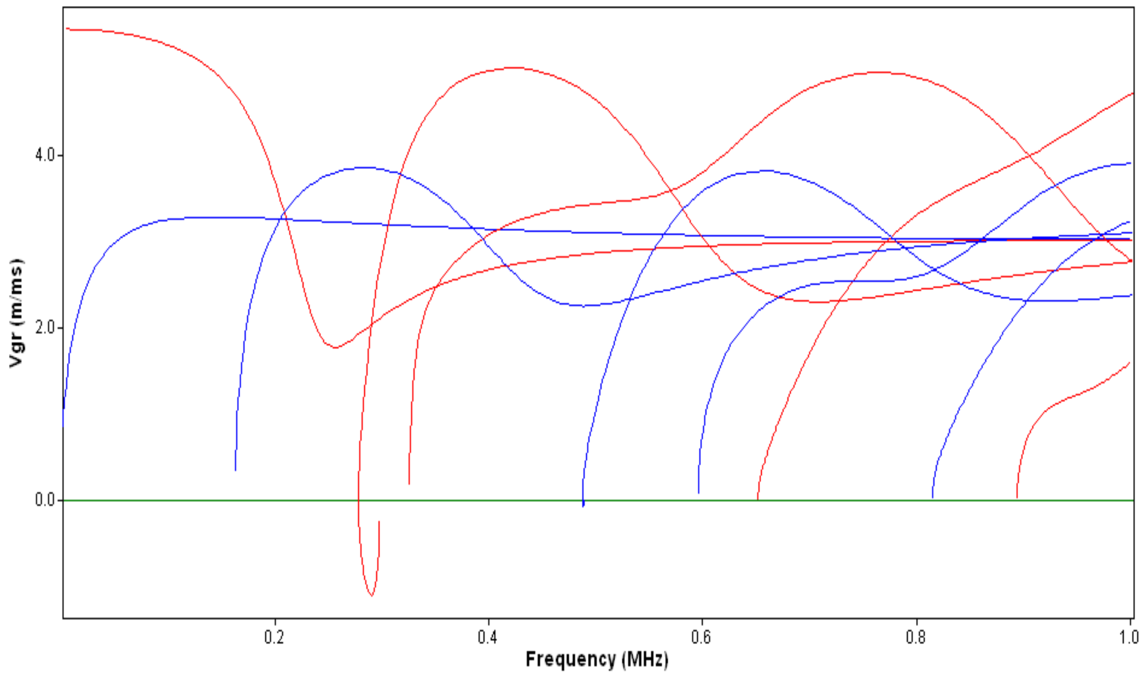


Figure 2.7: Group velocity vs Frequency Dispersion curves.

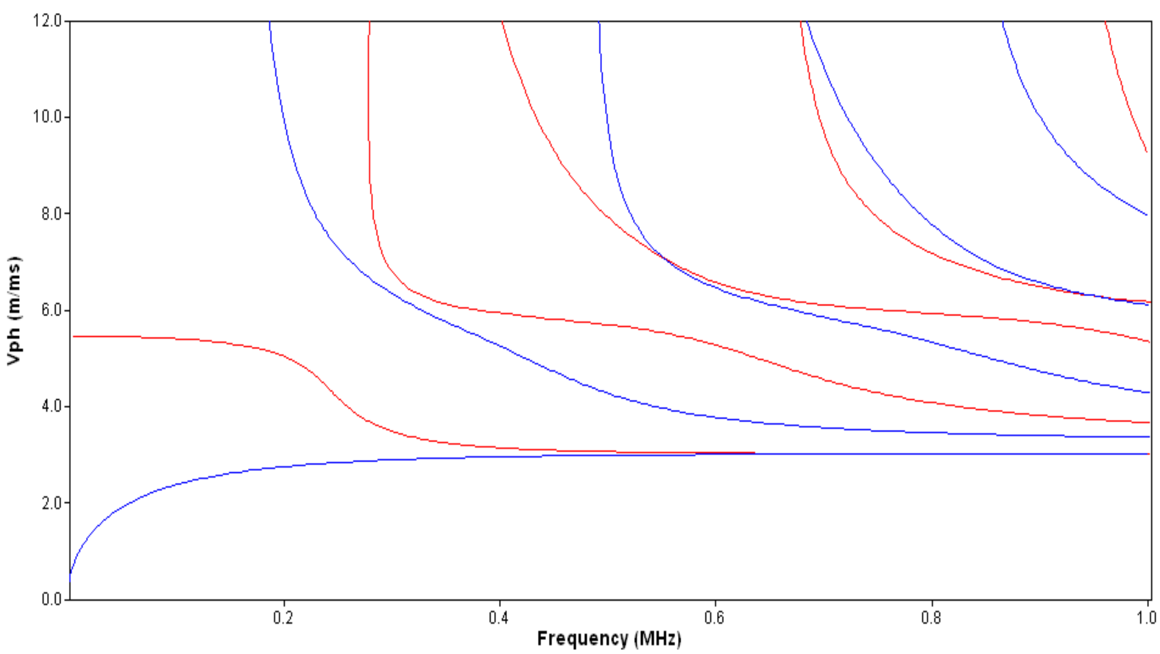


Figure 2.8: Phase velocity vs Frequency Dispersion curves.

Chapter 3

Wave Propagation Modelling

3.1 General

Numerical and analytical modelling of waves can be done with various methods. In these methods either time based or frequency bases techniques are used. In some cases it is hybrid also. In wave propagation very high frequency exciting forces are used. And as the system becomes mass dominated at very high frequency internal effects needs to be modelled very accurately.

3.2 Methods of Wave Propagation Modelling

Popular method of wave modelling are:-

1. Ray tracing method
2. Spectral element method(SEM)
3. Boundary element method(BEM)
4. Finite element method(FEM)
5. Distributed point source method (DPSM)

3.2.1 Ray Tracing Method

In this method the path of waves which are coming out from a point or group of points is traced as rays are coming through all interfaces. When only a few trains are of waves emerge and they are traversing through a simple interface this method gives desired results. One dimensional model based on ray tracing the wave movement's path, to make an insight to management issues of stress waves in graded material was developed by Bruck. H. Ray tracing method does not use time or frequency technique.[7]

Limitations

1. Only 1-D waves propagation can be modelled

2. Arbitrary forcing functions can't be solved

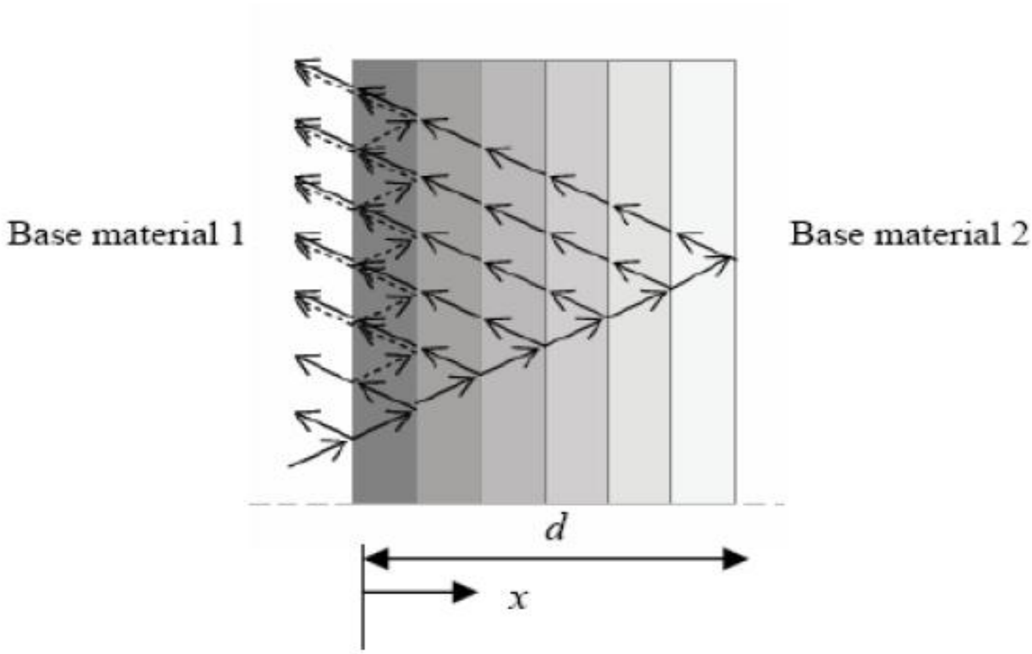


Figure 3.1: One dimensional Stress wave propagation through solid material [6].

3.2.2 Spectral Element Method (SEM)

To overcome the drawback of ray tracing method i.e. only 1-D wave modelling can be done, spectral element method (SEM) approach was developed by Doyle in 1989. In this method time forcing function is transformed into frequency function by Fast Fourier Transform (FFT).In this approach problems are solved in frequency domain and then time response is obtained using FFT and vice versa. Discretization is done where more number of interfaces are there like FEM. And the system matrix is generated for the whole structure using set of linear equations. In this method internal effects are represented exactly due to which exact solutions are obtained oftnely from transformed partial differential equation [8].

Limitations

1. Exact solution for complex differential equations are difficult to obtain, hence method becomes inefficient.

2. Not useful for transient waves.

3.2.3 Boundary Element Method

Boundary element method is a numerical modelling method in which initial value or boundary value are formulated using boundary integral equations. Boundary element method was discovered in 1970s. In boundary element method in context with FEM discretization is done only at the boundary of the element and with the help of integral function calculation are done. This method is computationally very fast as compared to SEM method [9].

Limitations:-

1. Not suitable for complex shapes.
2. Highly accurate in infinite domain.
3. Poor for 3D analysis.

3.2.4 Distributed Point Source Method (DPSM)

This method is based on spatial distribution of point sources. In this method the whole domain of the element is not meshed as in FEM but only surface or area of interest is meshed using point sources. To implement this model active surface of transducers are discretized to obtain an array of point source. This technique was discovered was B Placko and T Kundu in 2004 [10].

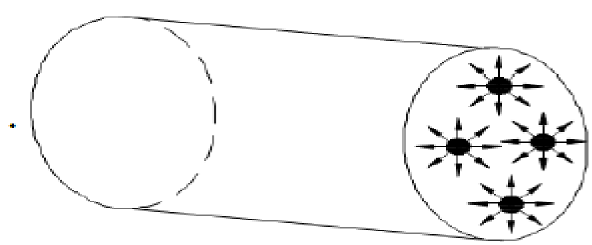


Figure 3.2: Discretization of transducer’s face [11].

In the first step, surface of transducer is first discretized into number of source points. The basic principle behind it is that the ultrasonic field generated by number of distributed point sources is summation of ultrasonic field generated by the main source.

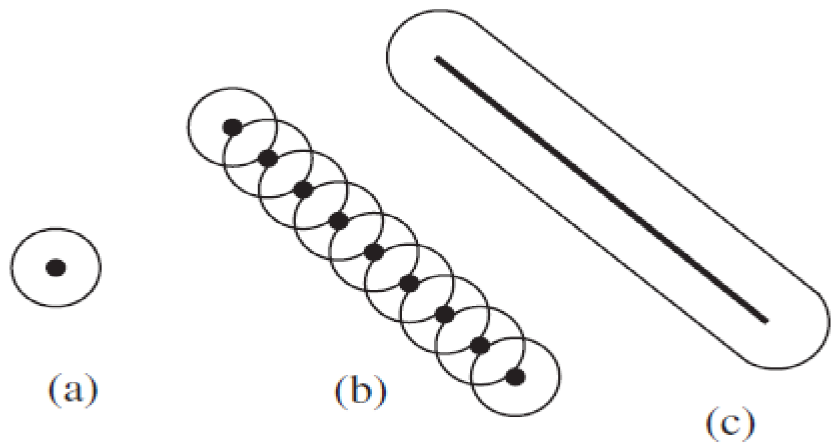


Figure 3.3: Source expanded in (a),(b) thick line. Source contracted thin line(c) [10].

A large number of point sources are placed side by side on plane surface, contracted and expanded position is shown in figure (b) points represent the contracted position and sphere represent the contracted position. Combine effect shown in figure 3.3. Only limitation with this method is that it is limited to ultrasonic waves only [5].

3.2.5 Finite Element Method

Finite element method is most versatile and conventional method. FEM method start developing in 1940 and by 1950 enormous development has been done in this field with applications in almost all the fields. In finite element method the whole domain is discretized into small-small modules which are known as finite element. In this method instead of solving the entire body problem in one operation a formulation for every single finite element is done and then added to get whole body solution [1]. Fem is very powerful tool to understand the fine details of wave modelling in solids**.** This modelling method is generally available in all commercial analysis tools like ABAQUS, ANSYS, LS-DYNA.

Advantages

1. FEM is capable of dealing with non-homogenity and non-linearity of solids.

2. FEM is useful for modelling of complex designs.
3. It is capable of testing entire structure in one measurement.
4. With FEM in accessible regions can also be tested in complex shapes.

Chapter 4

Literature Review

4.1 General

The application of ultrasonic guided waves in civil, mechanical, naval, offshore structures is increasing day-by-day. This chapter presents a brief literature about various domains in which research has been carried out in damage detection using ultrasonic guided wave and capability of FE method in detecting defects. This section also presents the current status of research.

4.2 Modelling of guided waves in ANSYS

Moser et al. 1999 presented applications of guided waves in detecting damages in the structures. Propagation characteristics of the wave were studied in the annular structures. Efficacy of the FEM technique was defined by validating the analytical results with experimental results and analytical results. Supermacy of FEM method over analytical method in case of complex structure is also stated [1].

Bartoli et al. 2005 used ABAQUS EXPLICIT to model UGW to model structural components. The aim was to model the vertical mode and studies its interaction with transverse type defects in railroad tracks. This model was used to study defects in long rail tracks. High frequency range of waves were modelled in the ABAQUS and were processed and examined with the help of wavelet transforms. Results were validated with the experimental data [11].

Kazys et al. 2006 studied the interaction of guided waves with welds, defects and other non-uniformities in liquid loaded steel plates. They investigated interaction of lamb waves in non-uniformities. They developed signal and data processing to visualize the dynamics of ultrasonic field over the plates and also the defects inside the plate were clearly visible. Commercially used finite element codes ANSYS and LS-DYNA were used in the study [13].

Banerjee and Kundu 2007 studied Distributed Point Source Method (DPSM) method of ultrasonic wave modelling to find out defects in steel plates immersed in fluids. Results clearly displayed that propagating guided waves were affected significantly by the presence of internal defects or cracks in the solid medium. DPSM results were also compared with the FEM results to show the superiority of DPSM. This technique was used to study defects in aluminium plates [10].

Han et al. 2009 presented a study in which they validated the simulated results generated with the help of ABAQUS with the experimental results. An isotropic aluminium plate with various temperature conditions were modelled in the FEM tool. The model was exited with different frequencies. Main idea was to check the accuracy of FEM tool in studying change in parameters i.e. temperature-dependent material properties. And the change in signal waveform was studied [14].

Jiangang Chen et al. 2010 proposed an approach to study early stage corrosion in the structures in wet or humid conditions. Authors proposed a way to detect corrosion using fundamental A_o wave in pulse-echo mode. In this work a new approach to eliminate the erroneous results generated when structure is surrounded by fluid medium is also demonstrated. Probability based diagnostic approach was used to evaluate numerically(ABAQUS) and experimentally generated results [15].

Mirahmandi and Honarvar 2011 presented various signal processing techniques to counter the dispersive behaviors of lamb waves. Low frequency S_o was generated using FEM based tools. Adjacent asymmetrical and symmetrical notches were generated and wave phenomenon was studied with the help of signal processing filter i.e. Wiener filtering and autoregressive spectral extrapolation. With the help of filter distance between two closely placed notches were detected [16].

Michele Sale et al. 2011 proposed an inverse procedure to calculate to find the elastic material constants of plates on the basis of GUW propagation. An optimization problem is also solved to reduce the discrepancy in dispersion curves generated using SAFE method and disperse. ANSYS was used to generate dispersion curves. The experimental results were generated using PZT/laser transducer. CWT was used to examine both experimental as well as numerical results [17].

Hanxin Chen et al 2012 generated a model in FEM using ANSYS to propagate UGW in a plate. Two dimensional elements were used to generate model. Analysis to detect crack in the geometry was done. FEM model was validated with experimental results. Modeling of TOFD technique using FEM to detect thick material is proposed [18].

Pistone et al. (2013) in this paper authors proposed a non-contact damage detection technique using guided ultrasonic waves generated by laser-pulser and received with an array of transducer. They represented analytical and experimental study. An FE model using ANSYS was generated to display the propagation of wave and leaky signal generated due to immersion of the plate in the fluid. Four defects were generated in the aluminium plate of 2.54mm thickness immersed in water. Signal processing was also used to study the damage-sensitive features [19].

Mitra and Gopalkarishanan (2016) presented a review paper on guided wave based structural health monitoring. This paper cited various applications of UGW in different industries. Various areas in which the development is taking place is also briefly mentioned. Authors has also highlighted various areas in which research can be done and various other directions where research can be further extended [20].

4.3 Closing Remarks

Review of literature have established the capability of lamb wave for damage detection in plate geometries with simulated damages in the form of cracks, notches and corrosion defects. Capability of Finite Element based simulation techniques is also proven in various publications. But very rare work is done to detect defect in submerged plate structures. Objective of the present work is to develop a model in FE based tool ANSYS and verify the fidelity of the model developed.

Chapter 5

Ultrasonic Wave Propagation in Plate in air

5.1 General

A rigorous study on generation of specific wave mode at a particular frequency in dry plates in ANSYS is presented in this chapter. Validation of generated results is also done with the experimentally generated results to prove the efficiency of the FEM modeling technique. The idea is to check whether procedure used to model ultrasonic guided wave in ANSYS is correct and wave modeled is showing the characteristic features i.e. group velocity, phase velocity, dispersion etc. of ultrasonic guide wave or not.

5.2 Modeling of guided wave in ANSYS

5.2.1 Numerical Setup

A 2-D plate model of 610mm*3mm dimension is developed in ANSYS v15.0 using time transient solution method. The plate is meshed using the two-dimensional (2D) four-node "PLANE 182" element having two degree of freedom per node [21]. The properties of Steel have been defined as: density(ρ)=7800kg/m^3, Young's Modulus E=210GPa, and Poisson's Ratio(ν)= 0.30. The size of the element is chosen using the formula given in equation (5.1).

$$l = \frac{\lambda_{min}}{20} \quad \ldots(5.1)$$

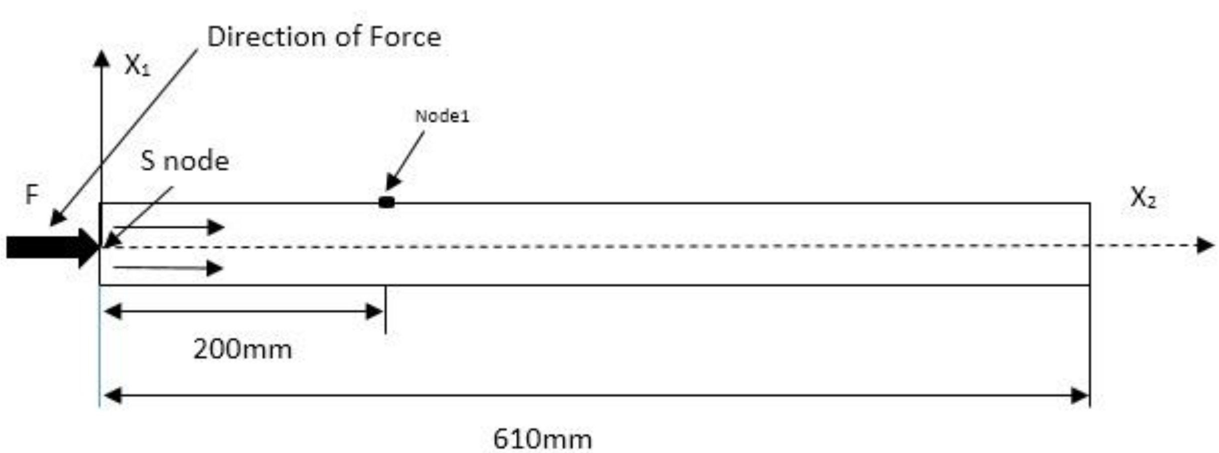
Where, λ_{min} is the shortest wavelength of wave of interest and l is the length of the element [1,16,17,18]. Temporal resolution is defined using the relation given in the equation (5.2):

$$\Delta t = \frac{1}{20 f_{max}} \quad \ldots(5.2)$$

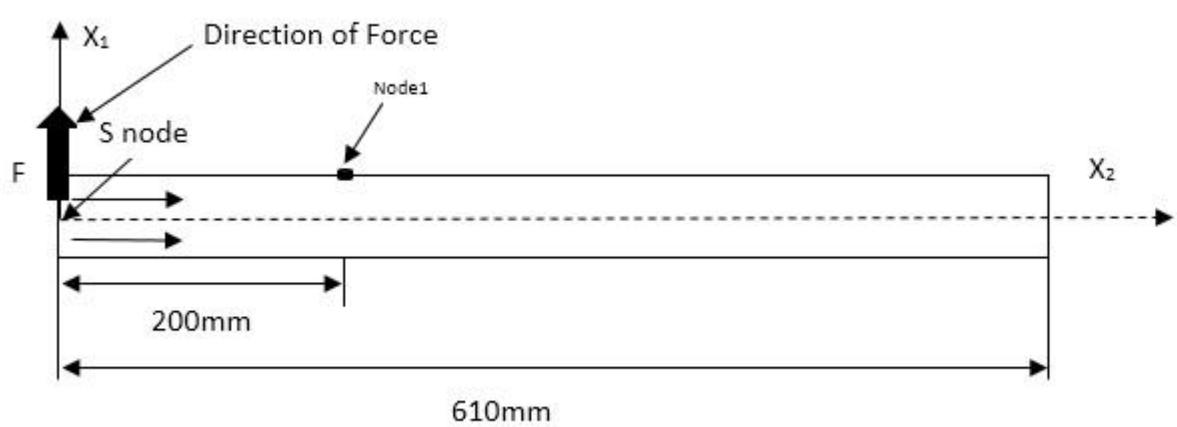
where, f_{max} is the maximum frequency of interest[1,16,17,18]. An implicit newmark procedure with decay factor of 0.005 and transient integration parameters α=0.25251 and δ=0.505 was used to perform time integration [16,18]. In the present work, owing to hardware constraint in the experimental setup, maximum frequency of 500kHz and a sinusoidal tone burst signal comprising of 5 cycles has been used. Time step has been taken as 0.02μs.

5.3 Simulation of Lamb Wave in dry Steel plate

To calibrate the model, a dry steel plate with cross section of 610mm*3mm size is subjected to loading. Two modes Symmetric and Anti-symmetric are excited selectively in the model by applying appropriate nodal displacements. To generate fundamental symmetric lamb



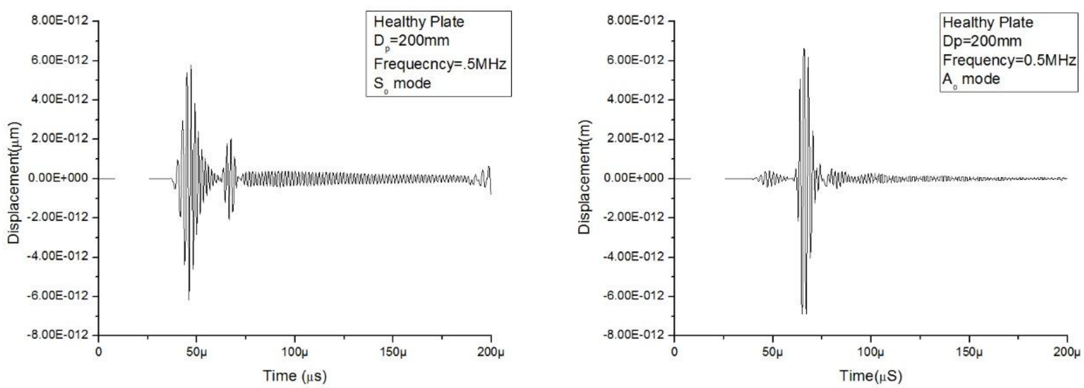
(a).



(b).

Figure 5.1: Loading patterns to generate (a) Fundamental Symmetric mode (b) Fundamental Anti-symmetric mode.

wave(S_o) in the plate forcing function of 500kHz frequency is applied parallel to surface of the plate on the left edge(Fig.5.1.a)[1,11,16,18].Similar loading function is applied on the same nodes in vertical directions to generate anti-symmetric wave (A_o) (Fig. 5.1.b)[11]..



(a) (b)

Figure 5.2: ANSYS simulation of UGW excited in dry steel plate by an impulse. (a). So mode (b). Ao mode.

Another point (shown as node1) is selected as the point where the response of the excitation has been observed. Node 1 is 200mm away from node S in X_2 direction. The distance propagated by the guided wave between source Node S and the response node 1 is termed as D_p (Propagation distance). Displacement responses at node 1 for both the modes are shown in Figure 5.2. Figure 5.2 (a) and (b) shows results of S_o and A_o respectively.

5.4 Experimental Validation of results

5.4.1 Experimental Set-up and Specimen Details

A mild steel plate of size 610mm*250mm*3mm has been used to perform experimental study. For ultrasonic testing, a UT system consisting of a Pulser-Receiver(PR) device (JSR make, Model DPR 300), ultrasonic transducers(Olympus, A301S, 0.5MHz), data acquisition card(Agilent Make) and LED computer display have been used (Fig 5.3). Pitch-catch method has been used to generate lamb wave in the subjected plate. A pair of inspection probe (Olympus Make) with rated frequency 0.5MHz has been used for wave generation. S_o and A_o mode has been generated using Perspex as interface between the transducer and the plate surface.

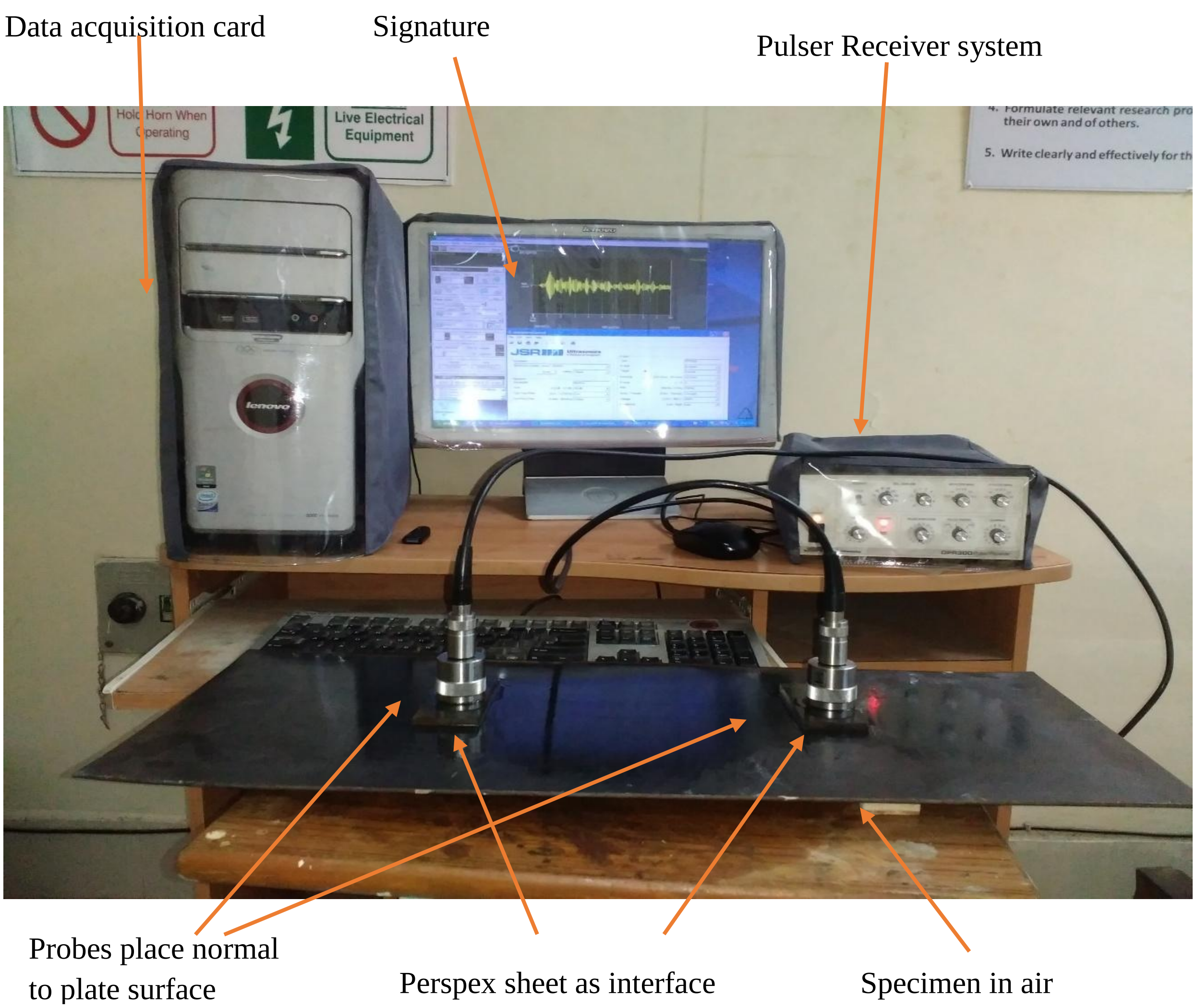


Figure 5.3: Experimental Setup.

To generate Symmetric mode transducers (transmitter and receiver) are placed at an angle of 31° to the normal to the plate surface with the help of Perspex semi-cylindrical shoe (Fig 5.4) of 30mm radius. For exciting pure A_o mode transducers are kept perpendicular to plate surface with Perspex sheet of 3mm thickness as an interface (Fig 5.3). The angle of incidence is calculated using disperse software and Snell's law. Incident angle vs Frequency graph is generated with help of Disperse software as shown in the Figure 5.5. At 0.5MHz frequency angle of incidence for exciting Symmetric mode is 31° using Perspex as interface between the transducer and plate. Similarly angle of incidence

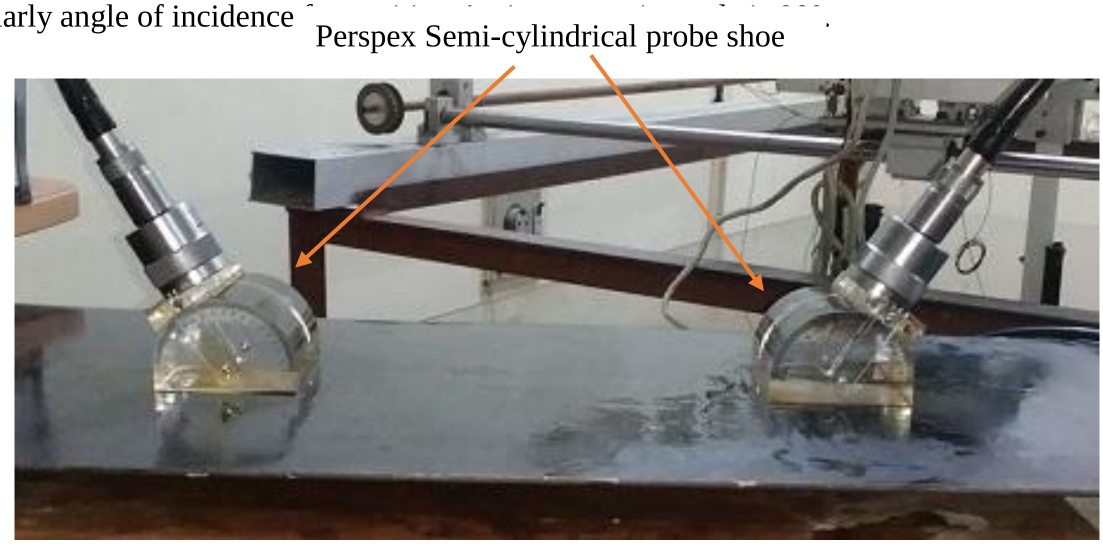


Figure 5.4: Transducer placement for S_o mode generation.

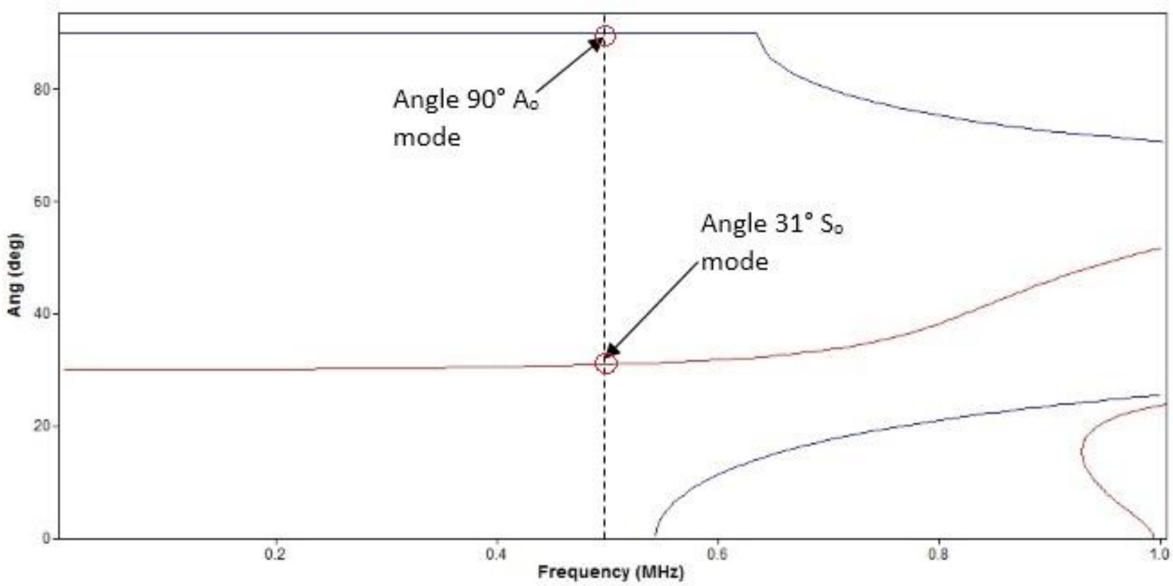


Figure 5.5: Incidence Angle vs Frequency Graph of 3mm steel plate.

5.5 Effect of Propagation Distance

Responses of the different ultrasonic guided wave modes propagating through the subject have been verified. In this section a study has been done to ensure that lamb wave modeled exhibit the characteristics of envisaged lamb wave. With increase in propagation distance (D_p) amplitude of the signal must decreases due to material attenuation and the time of arrival is expected to increase. In-plane(x-axis) and out-of-the plane(y-axis) displacements has been generated at different points namely 1,2,3,4 which are at 100, 200, 300, 400 mm from the point of excitation(shown as S) as shown Figure 4.6. Results generated using FEM tool are compared with analytical results. Group velocity of a wave is the speed at which overall shape of wave amplitude also known as envelope travels with change in propagation span. In this section group velocity (GV) of the propagating wave front at different locations (marked as 1,2,3,4 etc) has been evaluated by ratio of propagation distance and corresponding time of arrival from wave signatures.

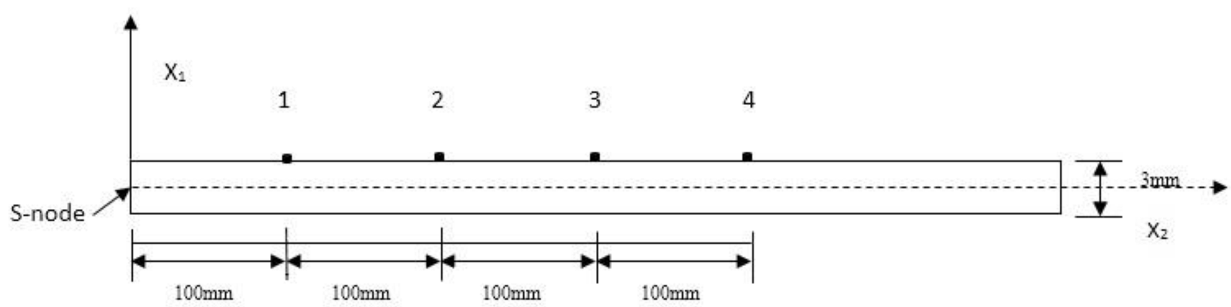


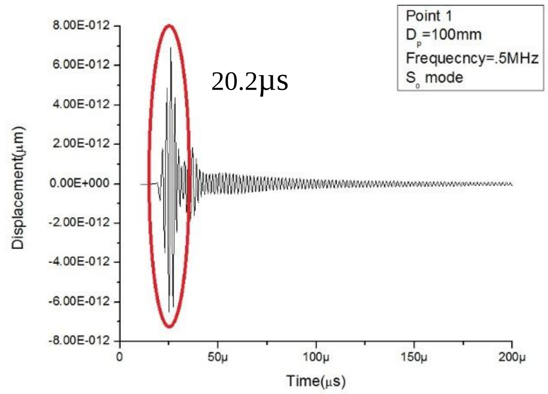
Figure 5.6: ANSYS model with various propagation spans.

.Group velocity is calculated using the given formula:

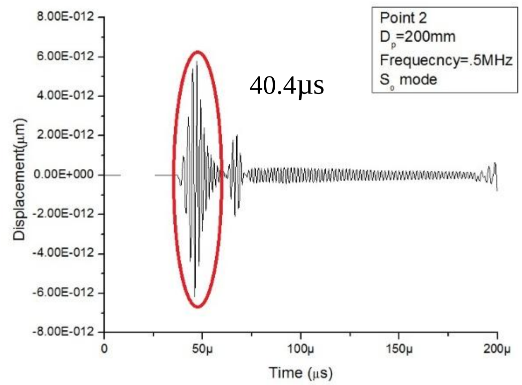
$$\text{Group Velocity} = \frac{D_P}{T} \qquad \ldots(5.3)$$

Where, D_p= Distance of propagation span (in mm)

T= Time of arrival of transmitted pulse.



(a).



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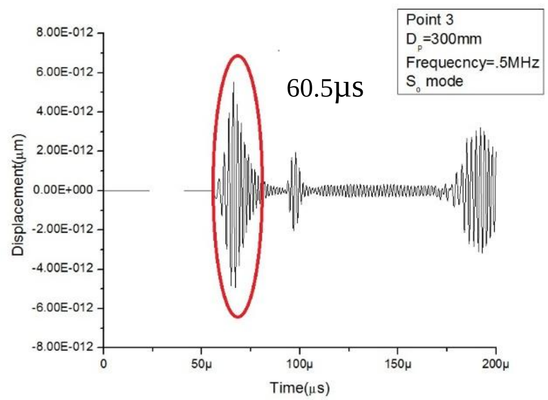
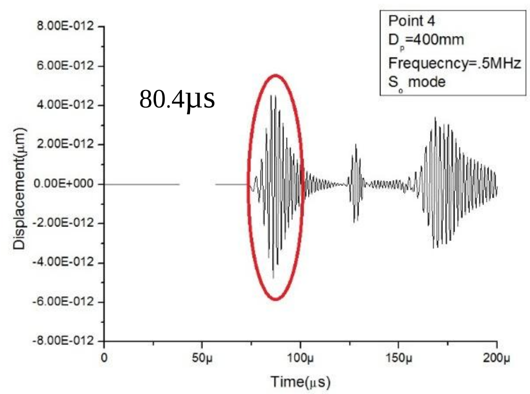
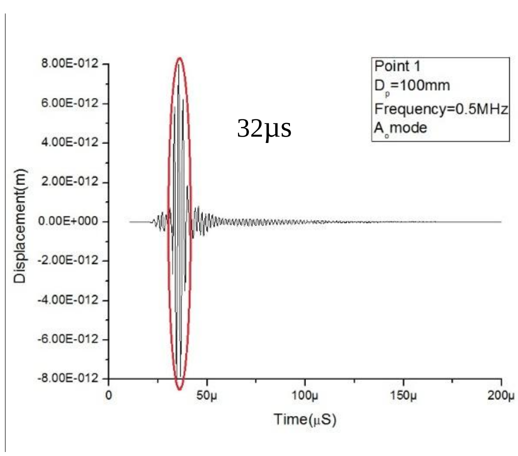


(c).

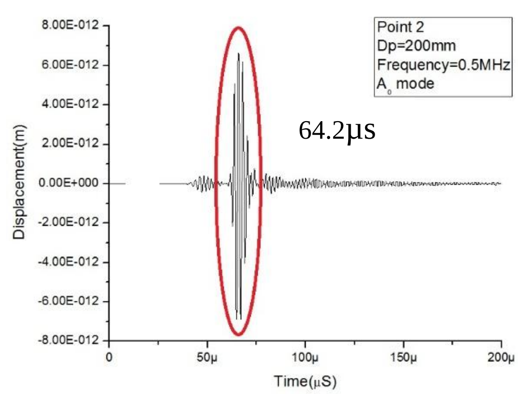


(d).

Figure 5.7: Displacement signature (ANSYS) with change in propagation span S_o mode.



(a)



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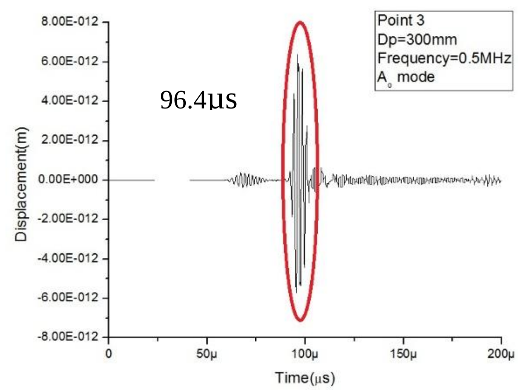

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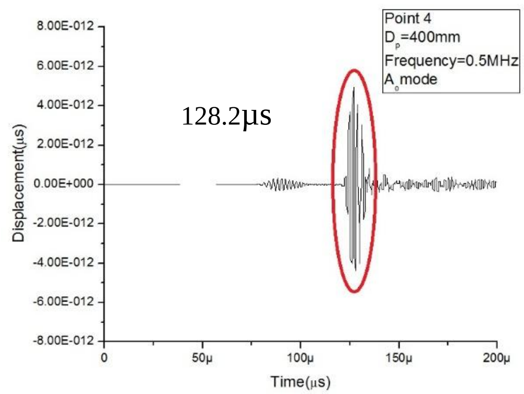


(d)

Figure 5.8: Displacement signature (ANSYS) with change in propagation span A_o mode.

Results shown in Figure 5.7 and 5.8 have been tabulated in table 5.1.

Table 5.1 Group Velocity of Modeled Wave

Point Marked in Figure	Propagation Span (mm)	Increment in position	S_o at .5MHz			A_o at .5MHz		
			Time of arrival (t) (μs)	Increment in time of arrival	Group velocity (D_p/t)	Time of arrival (t) (μs)	Increment In time of arrival	Group velocity (D_p/t)
1.	100	-	20.2	--	4.95	32	-	3.12
2.	200	100	40.4	20.2	4.95	64.2	32.2	3.11
3.	300	100	60.5	20.1	4.96	96.4	32.2	3.11
4.	400	100	80.4	20.2	4.97	128.2	32.2	3.12

Table 5.1 confirms that group velocity of the propagating wave fronts are consistent with respect to location of the receiver**.** Theoretical group velocity of these modes has also been obtained form Group Velocity Dispersion curves (Disperse software) as shown in Figure 5.9. At 0.5MHz frequency shown in Figure 5.9 GV of S_o mode is nearly 4.90 km/s and of A_o mode it is 3.27km/s which reasonably matches with results of table 5.1.

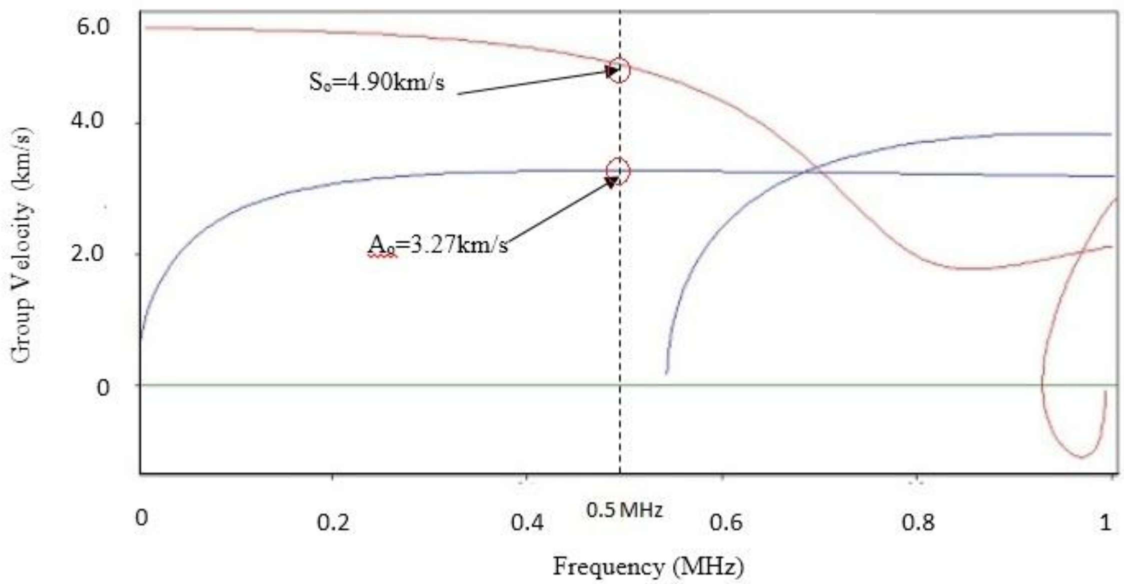
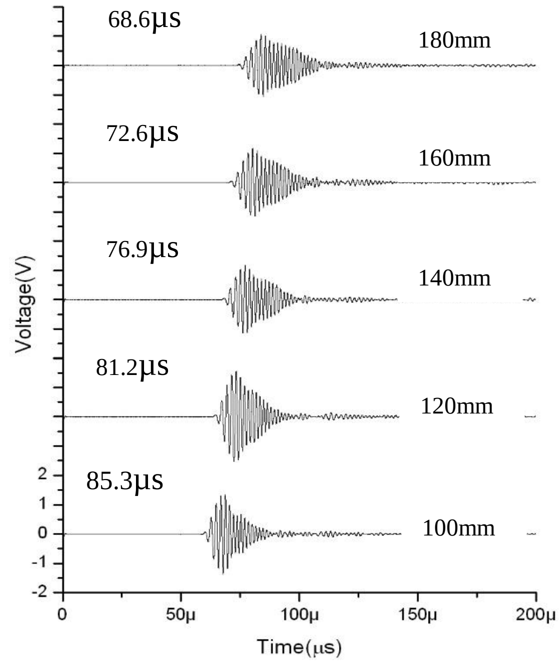


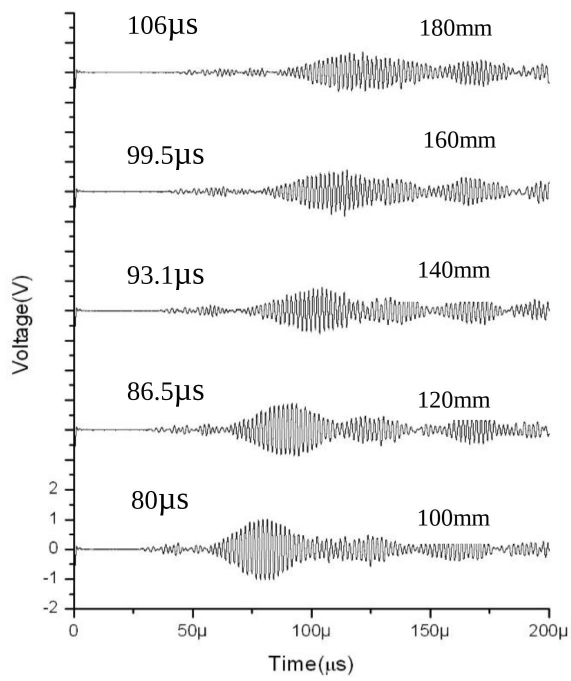
Figure 5.9: Group Velocity vs Frequency dispersion curves of 3mm dry steel plate.

Finally the response from the model has also been compared with the experimental results. To evaluate the group velocity of the propagating modes, corresponding guided modes have been excited and captured experimentally by using pair of transmitter and receiver transducer in the pitch catch orientation at appropriate angle of incidence mentioned in the section 5.4.1. In this experiment the transmitter is place at one fixed location and (representing point S in the ANSYS model Figure 5.1) whereas pulse transmission wave signatures have been captured at different locations(representing point 1,2,3,4 in ANSYS model).

However in the experimental setup, the receiver points have been considered at smaller increments (like 120, 140, 160, 180mm etc.). It has been done in order to avoid edge reflections from the side of the boundaries of the plate. Due to various experimental factors the experimental signatures obtained have slightly different characteristics shape which can be largely attributed to the dispersion effect due to finite band width of transducers used and also due to difference in wave form of the PR excitation.



(a). S_o mode at 0.5MHz



(b). A_o mode at 0.5MHz

Figure 5.10: Experimental Pulse Transmission (PT) signatures of propagating modes at different propagation distance.

Experimental results discussed above have been compiled in Table 5.2.

Table 5.2: Experimental Group Velocity with incremental span method

Propagation Span (mm)	Increment in position (ΔD_p)	S_o at .5MHz			A_o at .5MHz		
		Time of arrival (t) (μs)	Increment in time of arrival (Δt)	Exp. Group velocity	Time of arrival (t) (μs)	Increment in time of arrival (Δt)	Exp. Group velocity
100		68.6	--	--	80	--	--
120	20	72.7	4.1	4.87	86.5	6.5	3.07
140	20	76.9	4.2	4.76	93.1	6.6	3.03
160	20	81.2	4.1	4.87	99.5	6.4	3.10
180	20	85.3	4.1	4.87	106	6.5	3.07

$$\text{Group velocity} = \frac{\Delta D_p}{\Delta T} \qquad \ldots(5.4)$$

ΔD_p = Increment in propagation span

Δt = Increment in time of arrival

Numerical Group Velocity (ANSYS) of S_o mode 5km/s matches closely with theoretical GV 4.90km/s and experimental GV 4.87km/s in S_o mode. Also the numerical group velocity of A_o mode generated in ANSYS 3.12km/s matches closely with theoretical GV 3.27 km/s and experimental GV 3.07 km/s for A_o mode. Experimental group velocity is calculated using Equation 5.4, whereas analytical group velocities are calculated using Eq. 5.3. Group velocities of modeled wave matches well with the experimental group velocities and theoretical group velocities. Also with increase in propagation span there is a decrease in signal amplitude of the wave signature.

5.6 Effect of defect on wave propagation:

This section is focused on studying the interaction of the propagating modes with the discontinuities in the medium. For this purpose material removal in the form of notches has been studied. Results from the numerical model have been compared with the experimental results. In the model notches have been modelled as shown in Fig. 5.11. Whereas in the experimental study, notches have been machined as shown in Fig. 5.12. The extent of notch defect was increased and response from model and experimental data have been compared. The depth of the notch is varied with an increment of 0.5mm in different stages. At every step, behavior of the transmitted wave signature is studied and analyzed.

5.6.1 Numerical and Experimental setup and methodology

A notch 1.5 mm wide has been generated in the analytical model in ANSYS at a distance 100mm from the point of excitation S as shown in the Fig. 5.11. D_P has been consistently taken as 200mm in all cases. A point R-node 200mm from S-node is selected to receive the signal. Only depth of notches has been increased with every simulation from 0.5mm to 2.5mm. All other

Fig. 5.11: ANSYS model with notch defect.

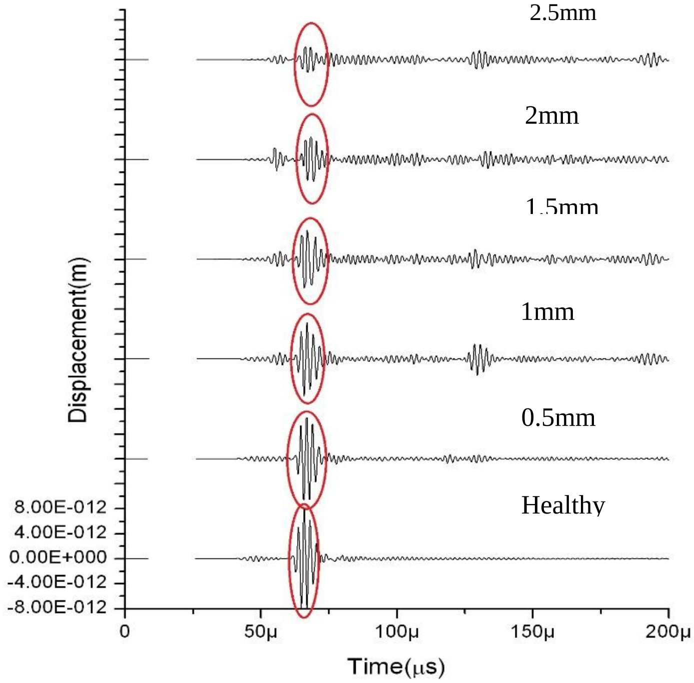
(a) Healthy plate (b) With Notch

Figure 5.12: Plate specimen healthy and with defect.

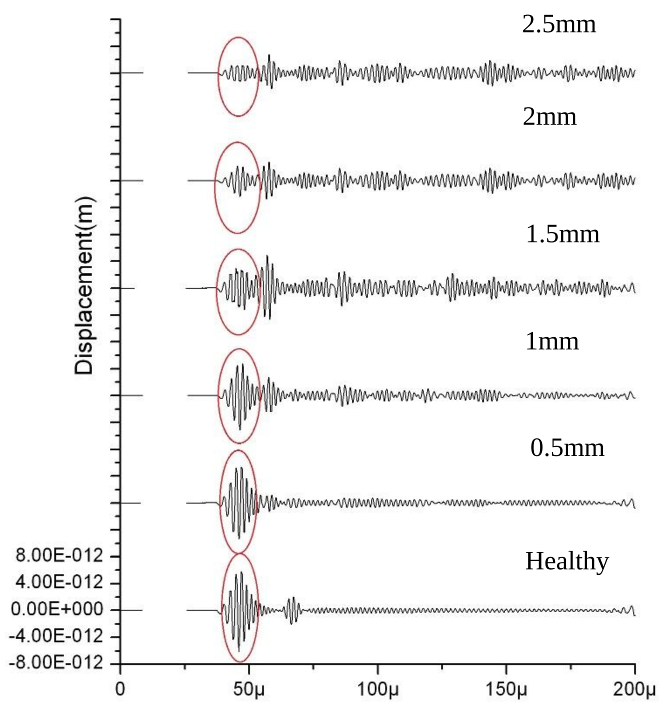
conditions and parameters are kept same as defined in Section 5.2. Similarly, in the experimental study, notches with varying depths has been seeded in the plate. Whereas all other experimental parameters have been retained as fixed. The ultrasonic probe and other UT characteristics are kept constant as defined earlier in section 5.4.1. Figure 5.12 shows the plate specimen without and with a machined defect.

5.6.2 Ultrasonic Pulse Transmission Investigation

Modification in the PT signatures are expected due to presence of flaws of varied extents in the plate. Each lamb wave mode is expected to behave differently to varying notches depth due to unique particle displacement and energy distribution across plate thickness. Fig. 5.13 and 5.14 shows the PT signatures captured using analytical model and experimentally respectively. A_o and S_o modes has been generated analytically as well as experimentally at frequency 0.5MHz. From the figure it is clear that with increase in depth of notch amplitude of the signal diminishes. It implies that with increase in depth of the notch energy is reflected back and amount of transmitted energy decreases. As anticipated earlier, owing to different characteristics lamb waves will behave differently to varying notch depths. Fig. 5.15 shows the graph, in which it is clearly visible that A_o and S_o modes behaves differently i.e. variation in amplitude due to notch depth is different. Graph also shows that behavior of S_o and A_o mode modelled in ANSYS is approximately similar to S_o and A_o mode though there is a difference in signal drop percentage. This also validates our model.

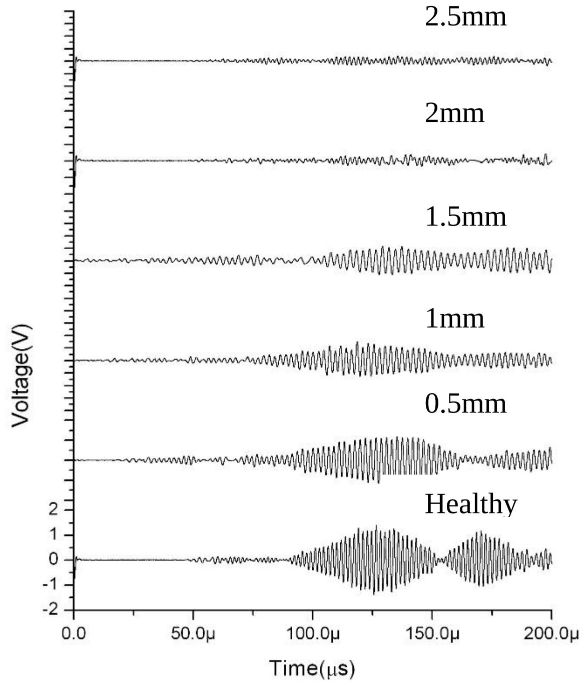


(a). A_o Mode

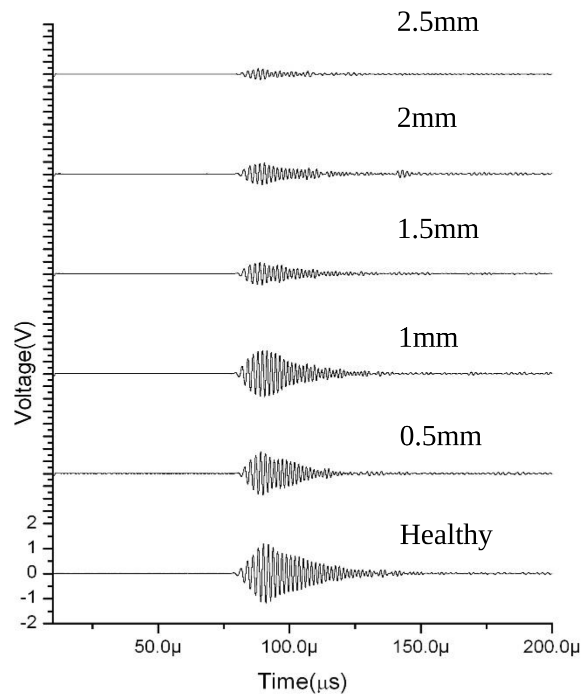


(b). S_o Mode

Figure 5.13: Interaction of Propagating wave modes (ANSYS) with notch defects of varying depths at 0.5 MHz.



(a) A_o Mode



(b). S_o Mode

Figure 5.14: Experimental PT signatures of pulse at all notch depths at 0.5MHz.

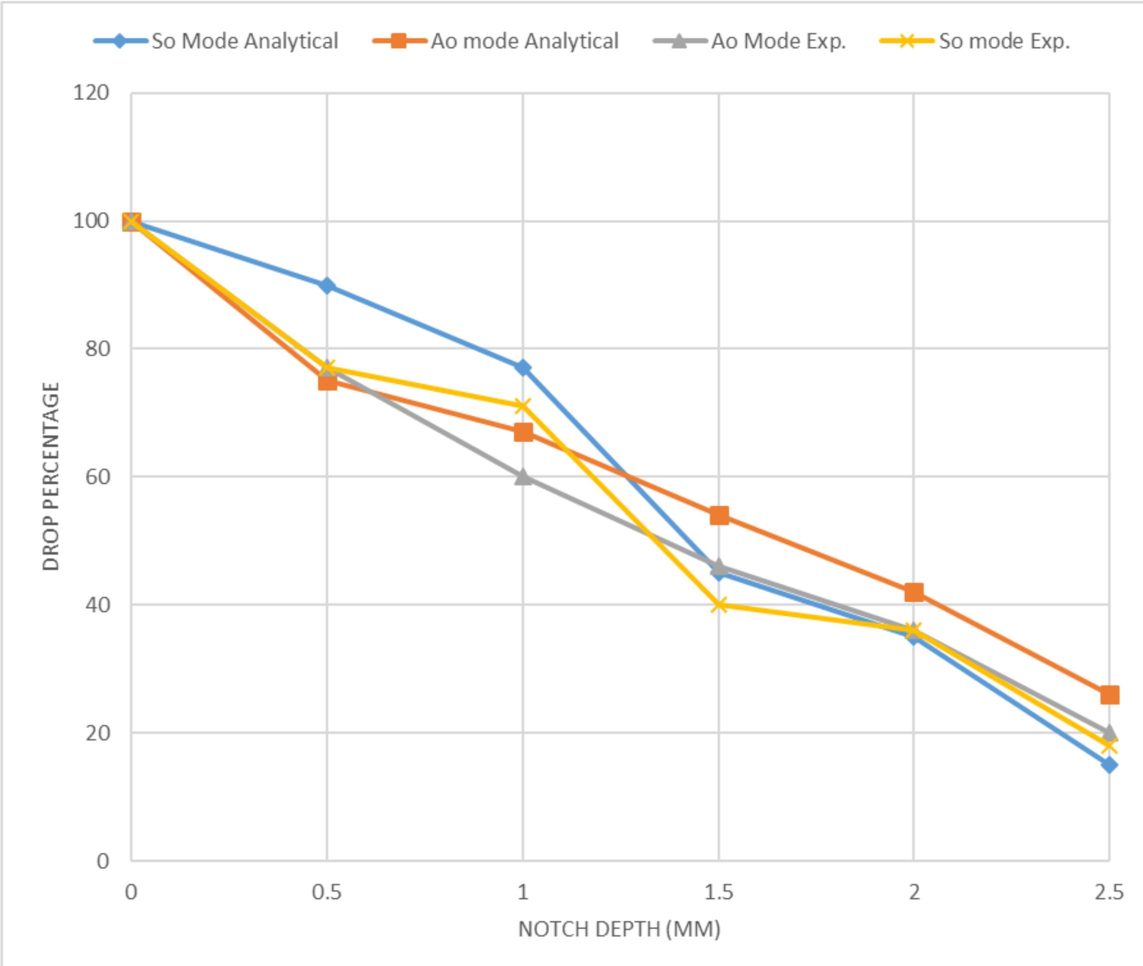


Figure 5.15: Variation in voltage amplitude with varying notch depths analytically and experimentally.

5.6.3 Mode Sensitivity:

As mentioned earlier, the amplitude of the transmitted pulse falls when there is any defect in the specimen. But decay in the amplitude is not uniform for all the wave modes. This distinguished behavior of lamb wave indicates that lamb wave lamb waves meets uniquely with every notch defect depending upon its depth. So understanding of this notch depth dependent behavior is important for application of suitable mode to detect extent of defect in a specimen. This mode specific interaction is termed as *Mode sensitivity*. It is very useful in detecting near surface and deep defects ranging up to the mid plane of the plate and beyond.

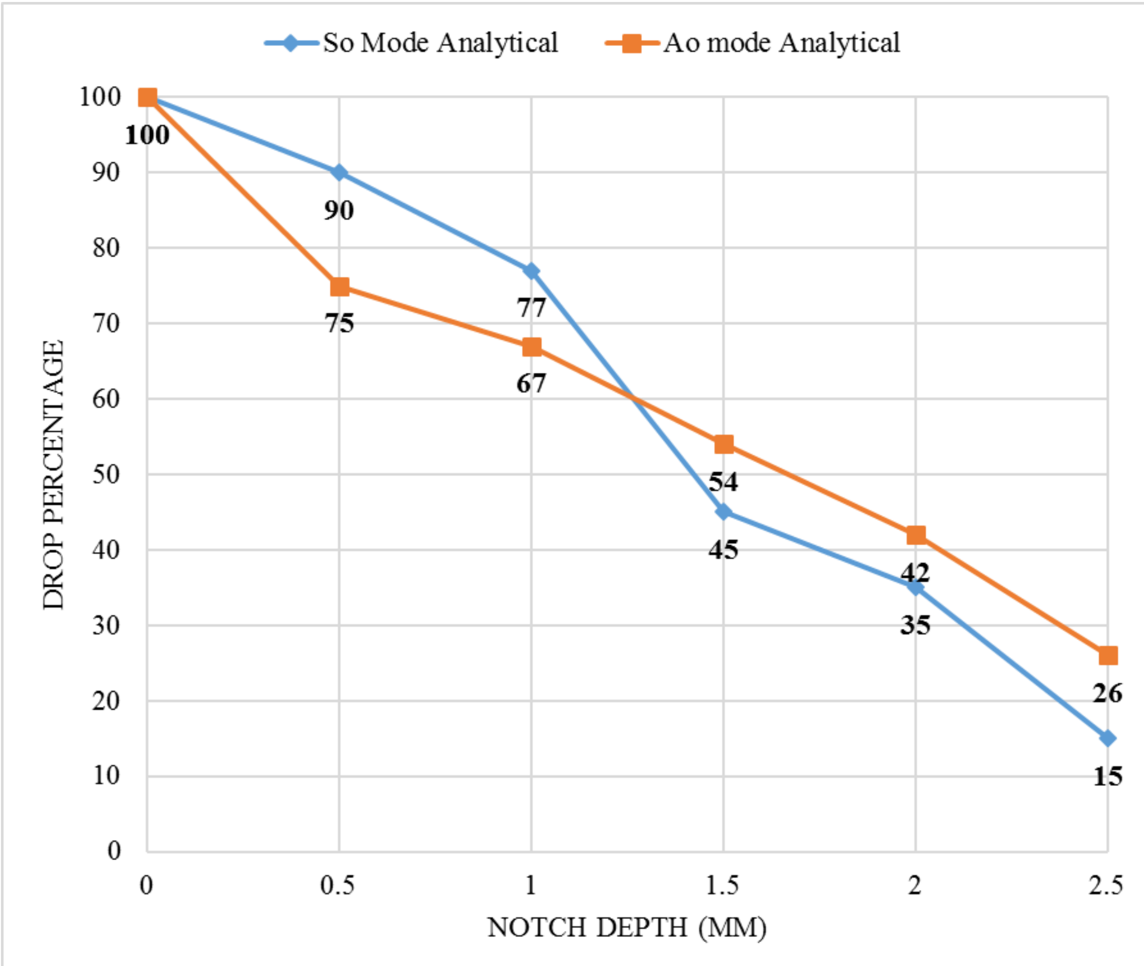
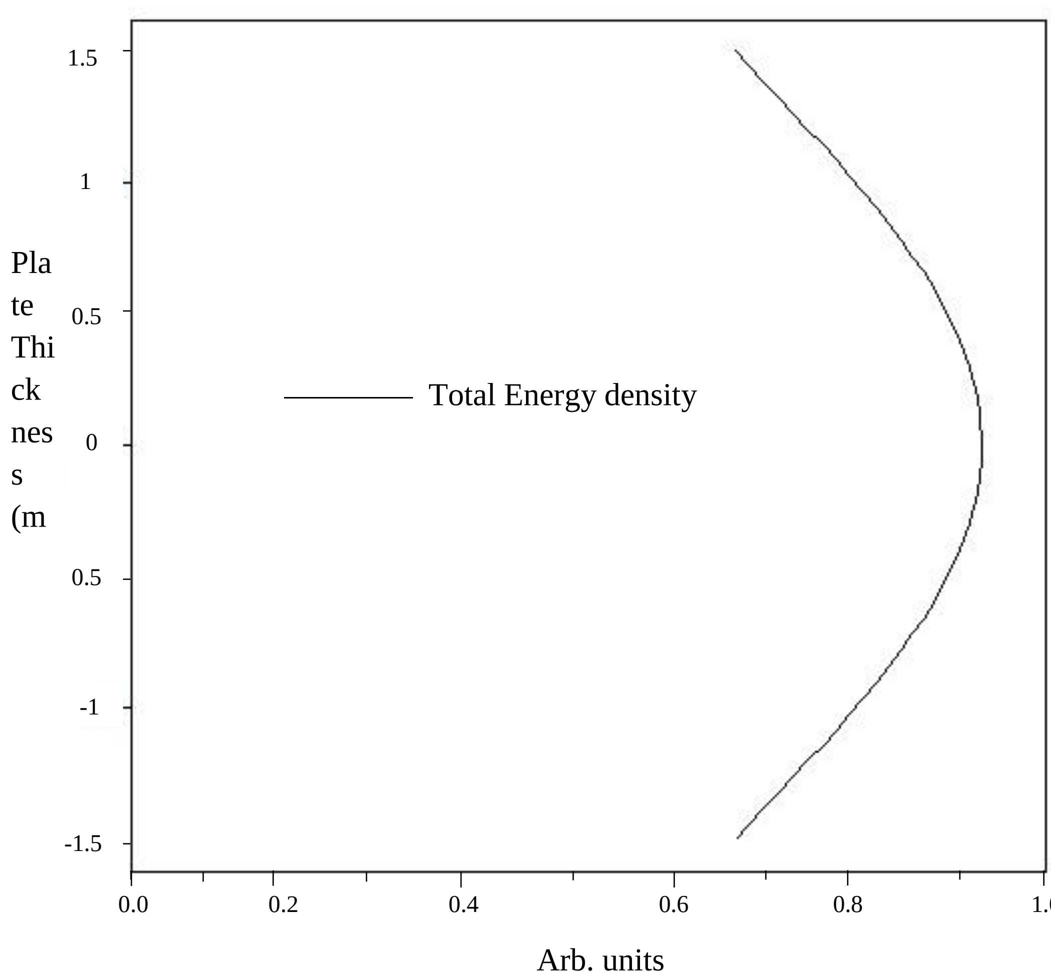


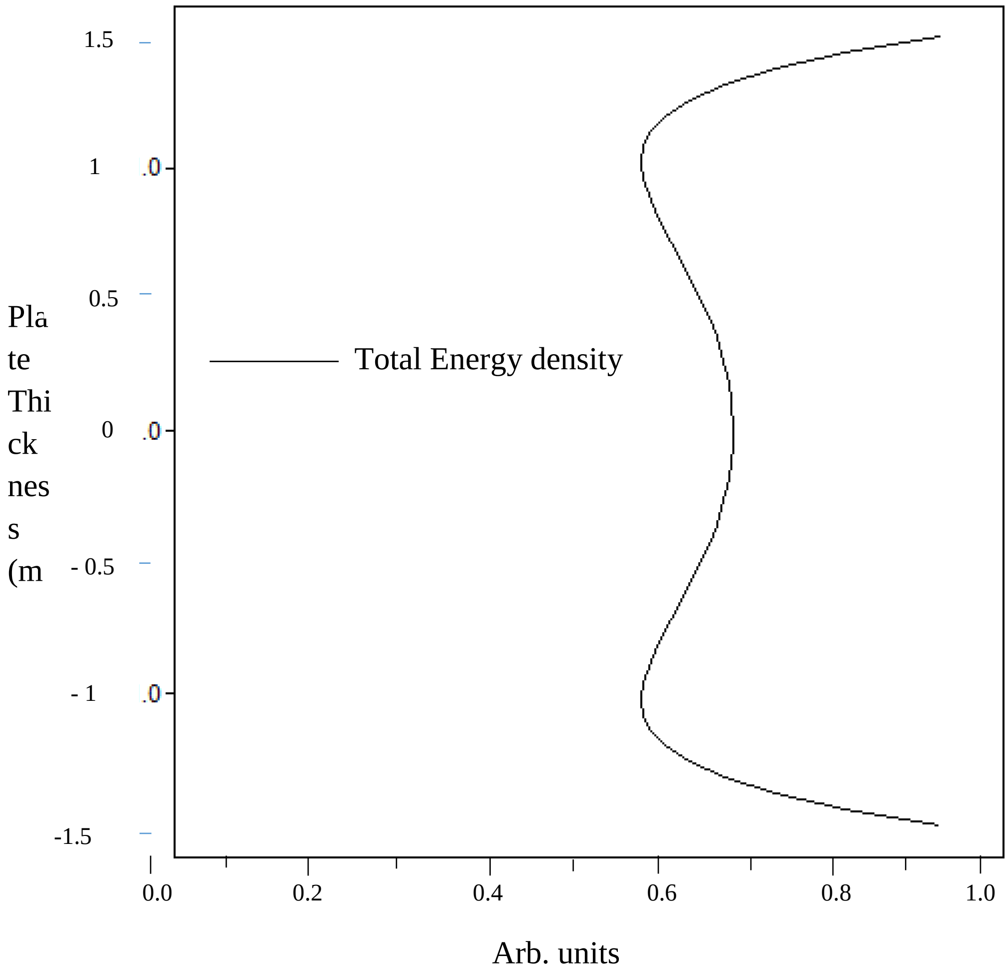
Figure 5.16: Drop in amplitude with notch size for selected modes at 0.5MHz.

Two lamb wave mode generated with FEM model in ANSYS environment are shown in the Figure 5.16. The value of signal without defect is taken as 100. Drop percentage in signal due to defect with respect to healthy plate signal is plotted in graph (Fig. 5.16). With the presence of 0.5mm defect in the model A_o exhibits a much higher loss (25%) as compared to S_o mode (10%). Similarly when notch depth is increased to 1mm there is marginal drop in both the modes A_o and S_o drops marginally to 67% and 77% respectively. But acute fall is observed in S_o mode when the depth is increased to 1.5mm. There is drop of 32% in the signal amplitude, whereas in A_o mode nominal drop is followed. With increase in depth both the modes as showing depreciation in signal at a normal rate. It can be concluded from this that S_o is insensitive to surface or shallow defects but sensitive towards deep defects whereas, A_o mode is sensitive to shallow defects and less

As shown in Fig. 5.17(a) S_o mode has significant energy distribution at the core than at the surfaces of the plate. It is more sensitive to core defects. And in A_o mode near the surfaces energy distribution is higher than that at the surfaces. There is a zig-zag flow of energy as shown in the figure there is increment in energy density at the core area also. So it can be concluded from it that A_o is highly sensitive to surface defects as compared to core defects. The trend followed by lamb wave generated in ANSYS is also validated with the mode sensitivity of the wave.



(a) S_o mode at 0.5MHz



(b). A_o mode at 0.5MHz

Figure 5.17: Wave Structure of Lamb wave modes.

5.7 Conclusion

This chapter was aimed at generating lamb wave modes in analytical simulation tool ANSYS. Characteristics of the lamb wave generated in the analytical tool were investigated by studying the effect of propagation distance on the lamb wave mode, group velocity of the modes, effect of notches with varying depth and mode sensitivity. The results were validated with tl d experimental results. The characteristics features of the modeled wave effectively matches with the experimental and theoretical results.

Chapter 6

Ultrasonic Wave Propagation in Plate Submerged in water

6.1 General

After developing a successful FEM model for lamb wave generation in dry plate in the preceding chapter. In this chapter a new FEM model using multi physics environment is developed to study the lamb wave propagation in submerged structure. As water is more attenuative then air, so the idea is to check the efficacy of the model and analyze the characteristics exhibited by the wave while travelling in a medium surrounded by water. A comparison between the analytical results and experimental results is also made to verify the fidelity of the model in damage detection.

6.2 Modelling of Lamb wave in ANSYS

6.2.1 Numerical Setup

Two dimensional model of plate of size 610mm*4mm immersed in water layer of 10mm thickness is modeled in the FE tool ANSYS v15.0 as shown in Figure 6.1. Four node “PLANE-182” element having two degree of freedom (x and y) per node is used to mesh steel plate. Water is meshed using two dimensional “FLUID 29” element having only one degree of freedom as pressure [21]. Density (ρ) of fluid is defined as 1000 kg/m^3 and sonic velocity as 1500m/s. Temporal and spatial resolution are defined using Eq. 5.1 and 5.2.

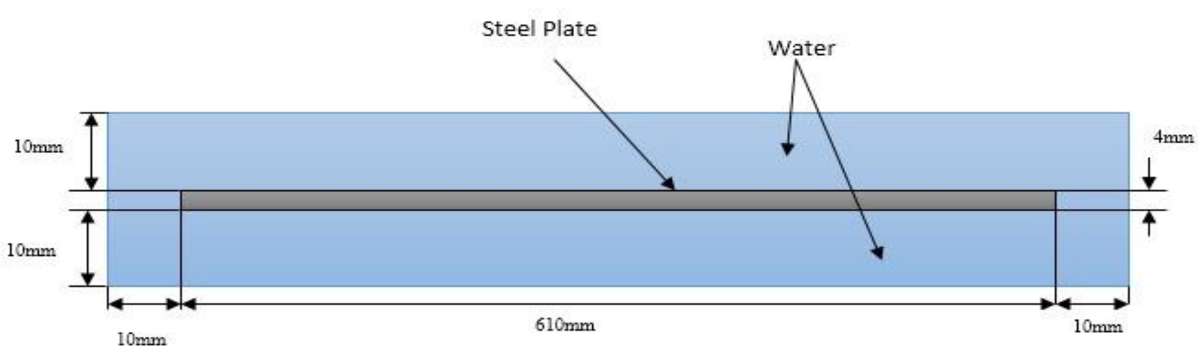


Figure 6.1: ANSYS model of plate immersed in water.

Properties of steel are defined same as in Section 5.2.1 of previous chapter. Boundary conditions at interface (FSI) are defined by using proper flags in ANSYS. At liquid domain, FLUID 29 elements exhibits only pressure degree of freedom. But, for the FSI elements displacements parallel and perpendicular to plate surface are allowed [19]. All other parameters are same as defined in Section 5.2.1 of previous chapter. Owing to computational system constraint frequency of 0.5MHz is used to excite the structure.

6.3 Simulation of Lamb wave in submerged Steel plate:

A 610*4mm steel plate submerged in 10mm layer of water is excited by applying load at node S as shown in Fig. 6.2. Same loading patterns are used to excite fundamental lamb wave as defined in Section 5.3 of previous chapter. A point (shown as node 1) 200mm from S point is selected to observe the response of the signal. Displacement responses of both wave modes Symmetric and anti-symmetric are shown in Figure 6.4 (a) and (b) respectively.

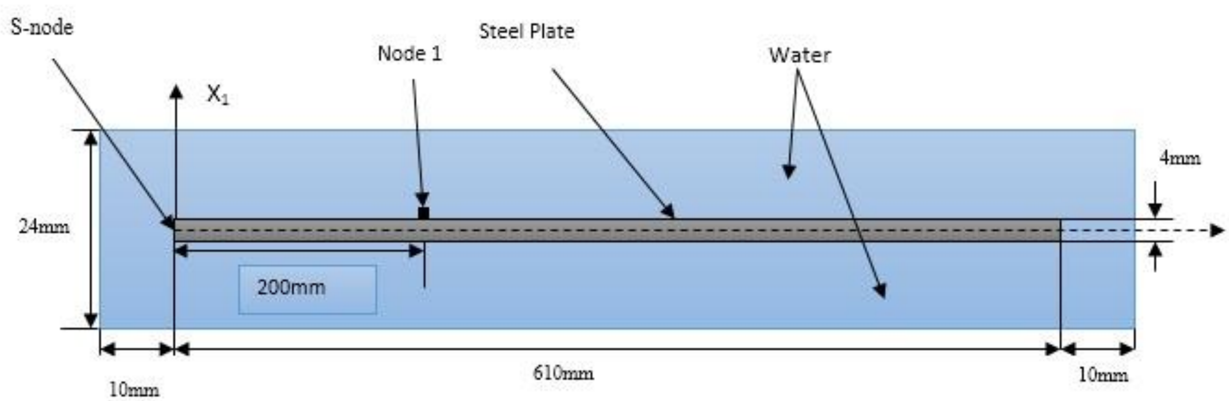
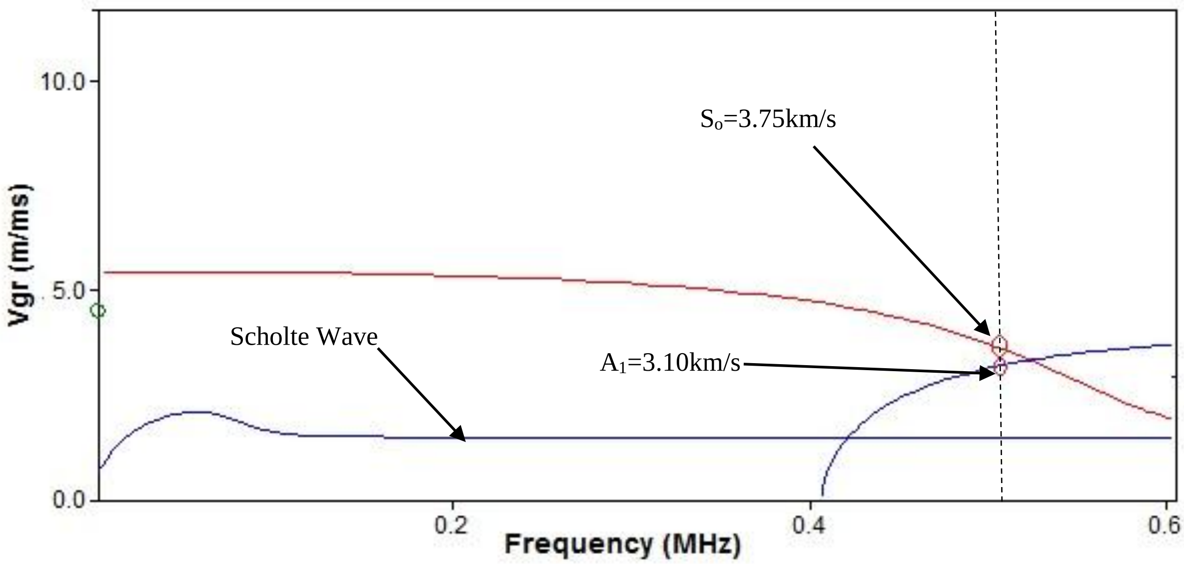


Figure 6.2: Points definition to excite fundamental waves in the structure.

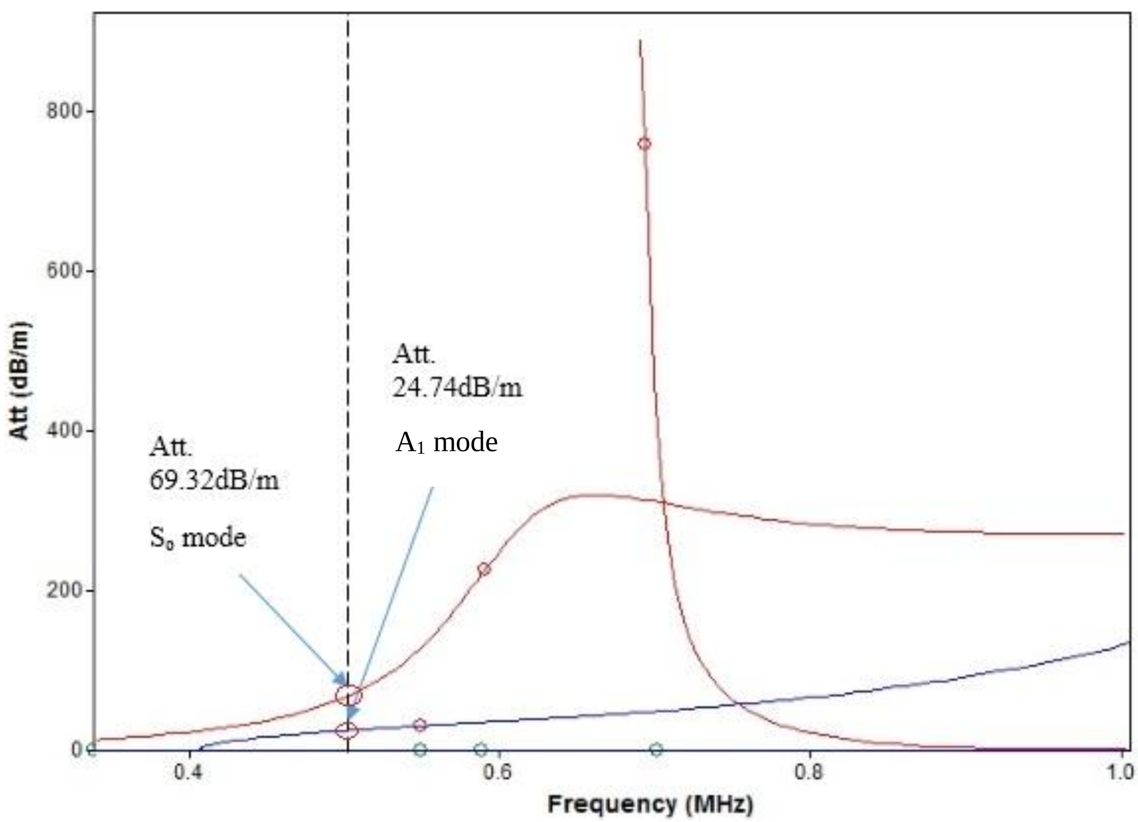
From the Dispersion curves (Figure 6.3) at 0.5MHz frequency following observations are made:

- When plate is submerged, Scholte wave transverses at the interface of steel and water. Phase velocity is almost equal to bulk wave velocity. Scholte wave is non-attenuative. This mode exits only in case when plates are submerged in water.

- Anti-symmetric (A_o) mode due to substantial loss of energy due to its lateral motion over entire range is not apparent in dispersion curves.

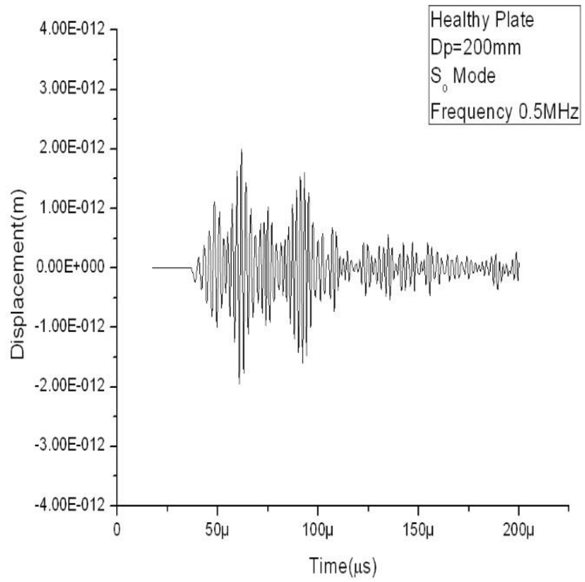


(a). Group Velocity vs Frequency

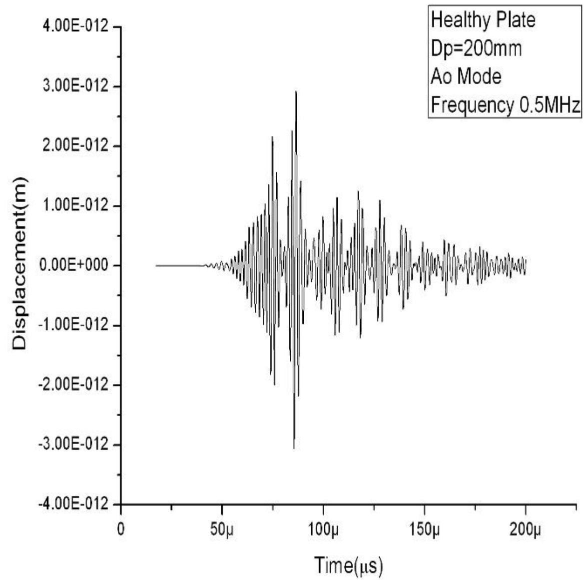


(b). Frequency vs Attenuation graph

Figure 6.3: Dispersion curves for 4mm steel plate in water.



(a).



(b).

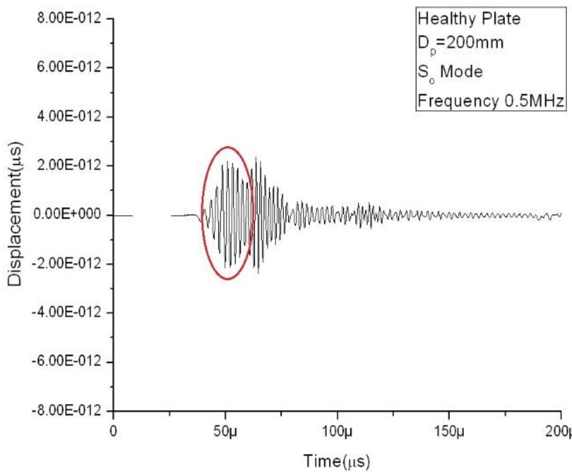
Figure 6.4: ANSYS simulation of Lamb excited in plate submerged in water.(a) S_o mode (b) A_1 mode.

6.4 Experimental validation of results

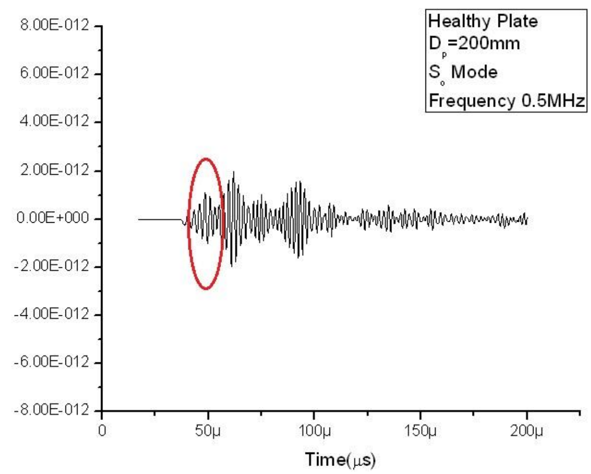
For experimental validation of results a publication by Sandeep Sharma and Abhijit Mukherjee is used [22].

6.5 Attenuation due of immersion of structure

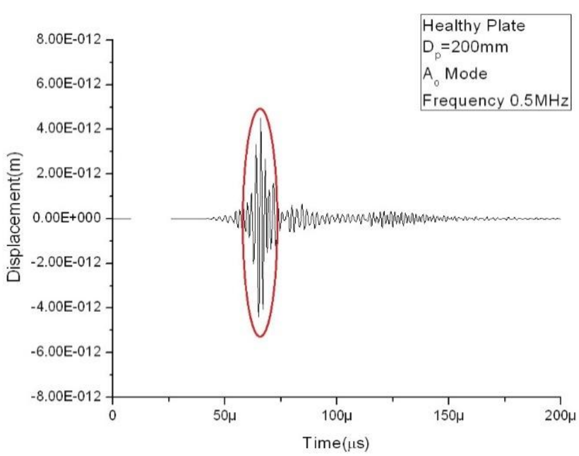
With the presence of water around the structure, there is attenuation in the signal as shown in the Fig. 6.3(b), which is due to leaky lamb waves, ultrasonic waves which transmits to the water are called 'Leaky Lamb waves". Whereas attenuation in structure in air exhibits negligible or no attenuation due to its surroundings. It implies that amplitude of signal at same node under different conditions (dry or wet) should be different. So a comparison of signal response has been done at a node 200mm from the s-node or source node in dry plate and in submerged plate as shown in Fig. 6.5. It is clearly observed form the figure that with the immersion of plate structure in water, attenuation is higher due to leakage of signal to the surroundings. This verifies that FE model exhibits attenuation due to leaky lamb waves.



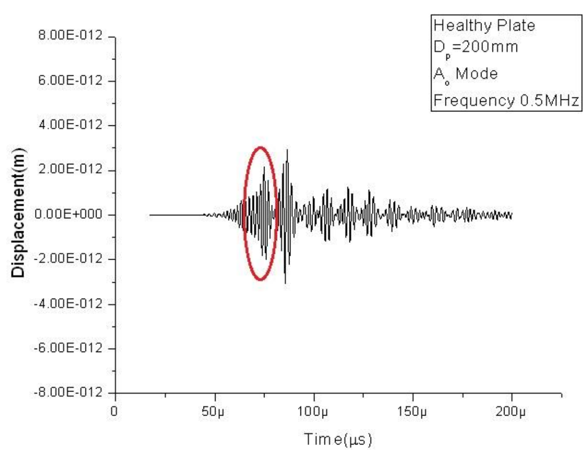
(a). Plate in air(S_o)



(b). Plate in water(S_o)



(c). Plate in air(A_1)

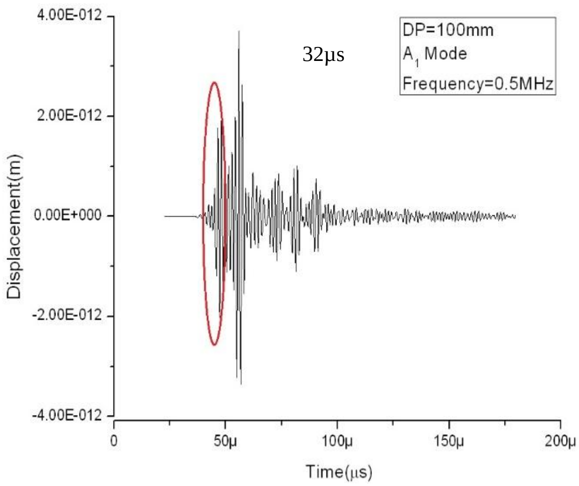


(d). Plate in water(A_1)

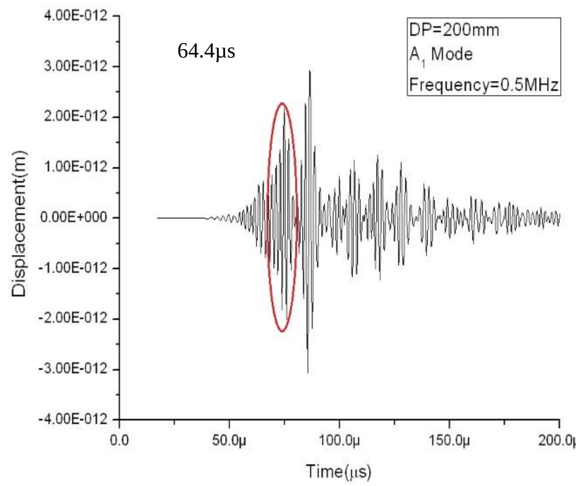
Figure 6.5: Effect of attenuation due to water in S_o mode (a,b) and A_1 mode (c,d).

6.6 Effect of Propagation Distance

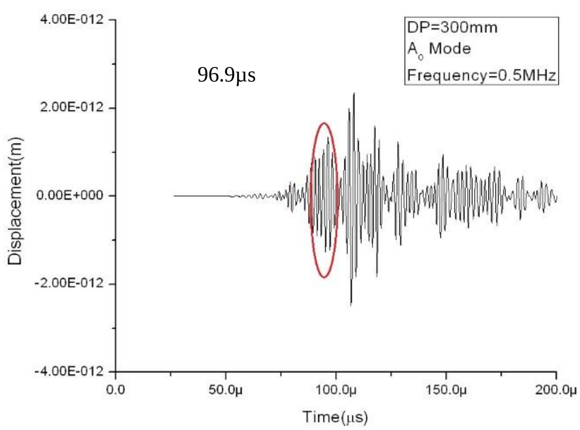
Drop in the signal amplitude with submersion of plate in water verifies our model in one parameter of signal attenuation. In this section another parameter “effect of propagation distance” is studied. As discussed in section 5.5 of previous chapter with increase in propagation span (Dp) amplitude of signal is expected to drop due to material attenuation, leaky lamb waves (signal refracted/leaked to water) and time of arrival is also expected to increase. In plane and out of plane displacements has been generated at different points at a span of 100 mm as in section 5.5. Different points at uniform distance of 100mm has been selected to study the response (Fig. 6.6, 6.7). Equation 5.3 is used to calculate Group velocity of the wave.



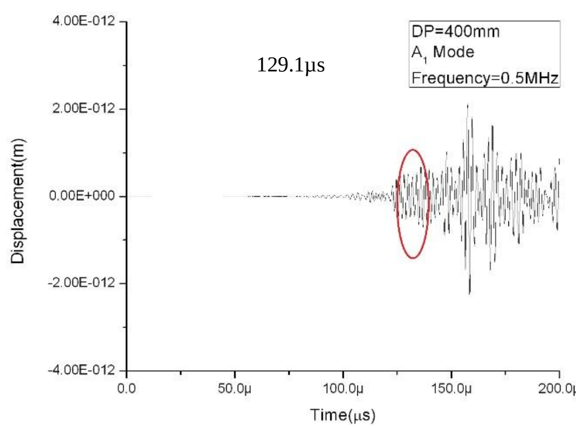
(a)



(b)



(c)



(d)

Figure 6.6: Displacement Signatures (ANSYS) with change in propagation span A_1 mode at 0.5MHz.

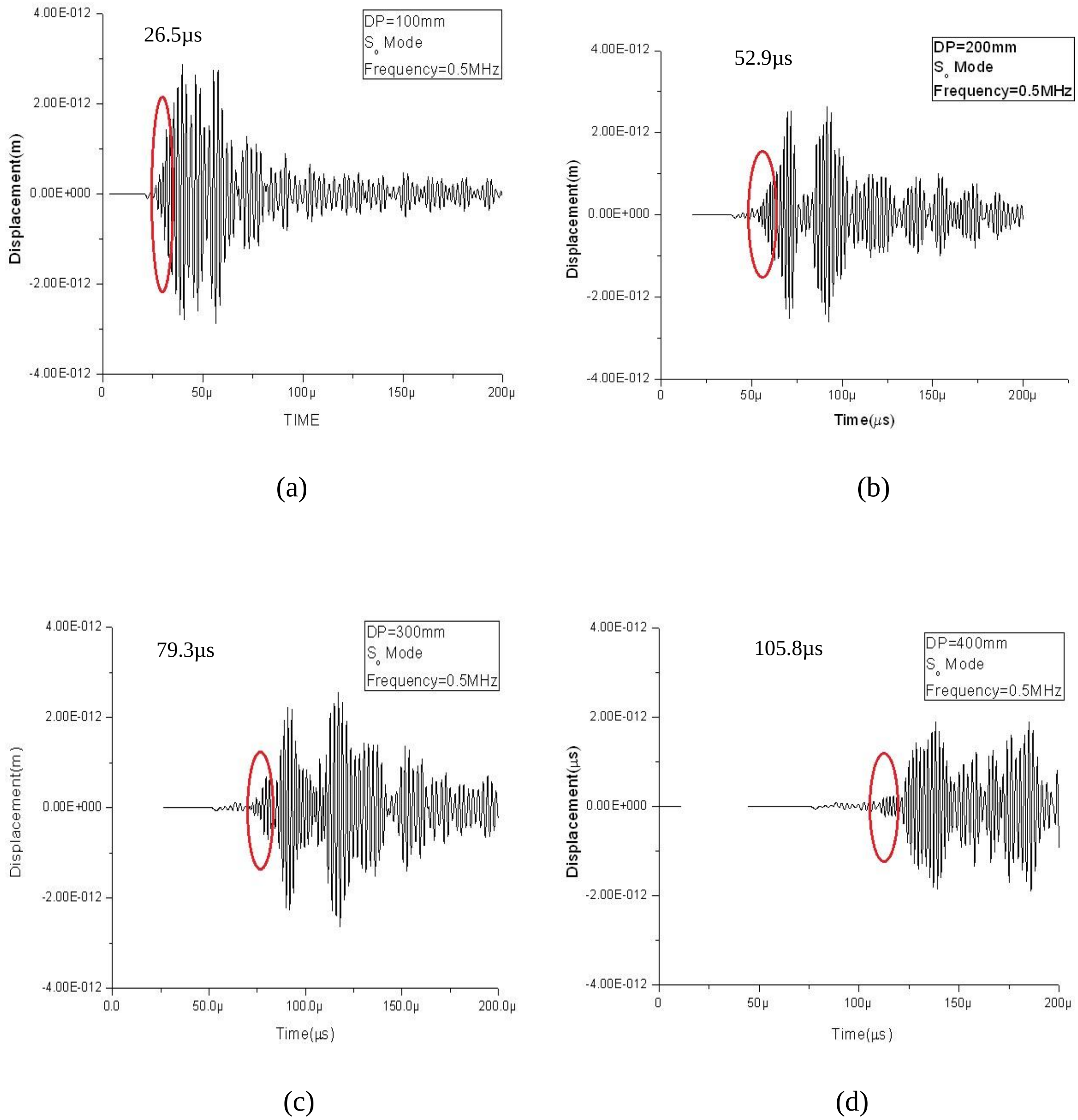


Figure 6.7: Displacement Signatures (ANSYS) with change in propagation span S_o mode at 0.5MHz.

Results shown in the Figure 6.6 and 6.7 are tabulated in the table 6.1.

Table 6.1 Group velocity of Modeled Wave

Point Marked in Figure	Propagation Span (mm)	Increment in position	S_o at .5MHz			A_1 at .5MHz		
			Time of arrival (t) (µs)	Increment in time of arrival	Group velocity (D_p/t)	Time of arrival (t) (µs)	Increment In time of arrival	Group velocity (D_p/t)
1.	100	-	26.5	--	3.77	32	-	3.12
2.	200	100	52.9	26.4	3.80	64.4	32.4	3.09
3.	300	100	79.3	26.5	3.77	96.9	32.5	3.08
4.	400	100	105.8	26.4	3.78	129.1	32.2	3.10

Table 6.1 confirms that group velocity of the propagating wave fronts are consistent with respect to location of the receiver. Theoretical group velocity of these modes has also been obtained form Group Velocity Dispersion curves (Disperse software) as shown in Figure 6.3(a). At 0.5MHz frequency shown in Figure 5.9 GV of S_o mode is nearly 3.75 km/s and of A_1 mode it is 3.10km/s which reasonably matches with results of Table 6.1.

6.7 Effect of defect on wave propagation

This section is focused on studying the interaction of the propagating modes with the discontinuities in the medium. For this purpose material removal in the form of notches has been studied. Results from the numerical model have been compared with the experimental results. In the model. Notches have been modelled as shown in Fig 5.11. The extent of notch defect was increased and response from model and experimental data have been compared. The depth of the notch is varied with an increment of 0.5mm in different stages (Fig. 6.8). At every step, behavior of the transmitted wave signature is studied and analyzed.

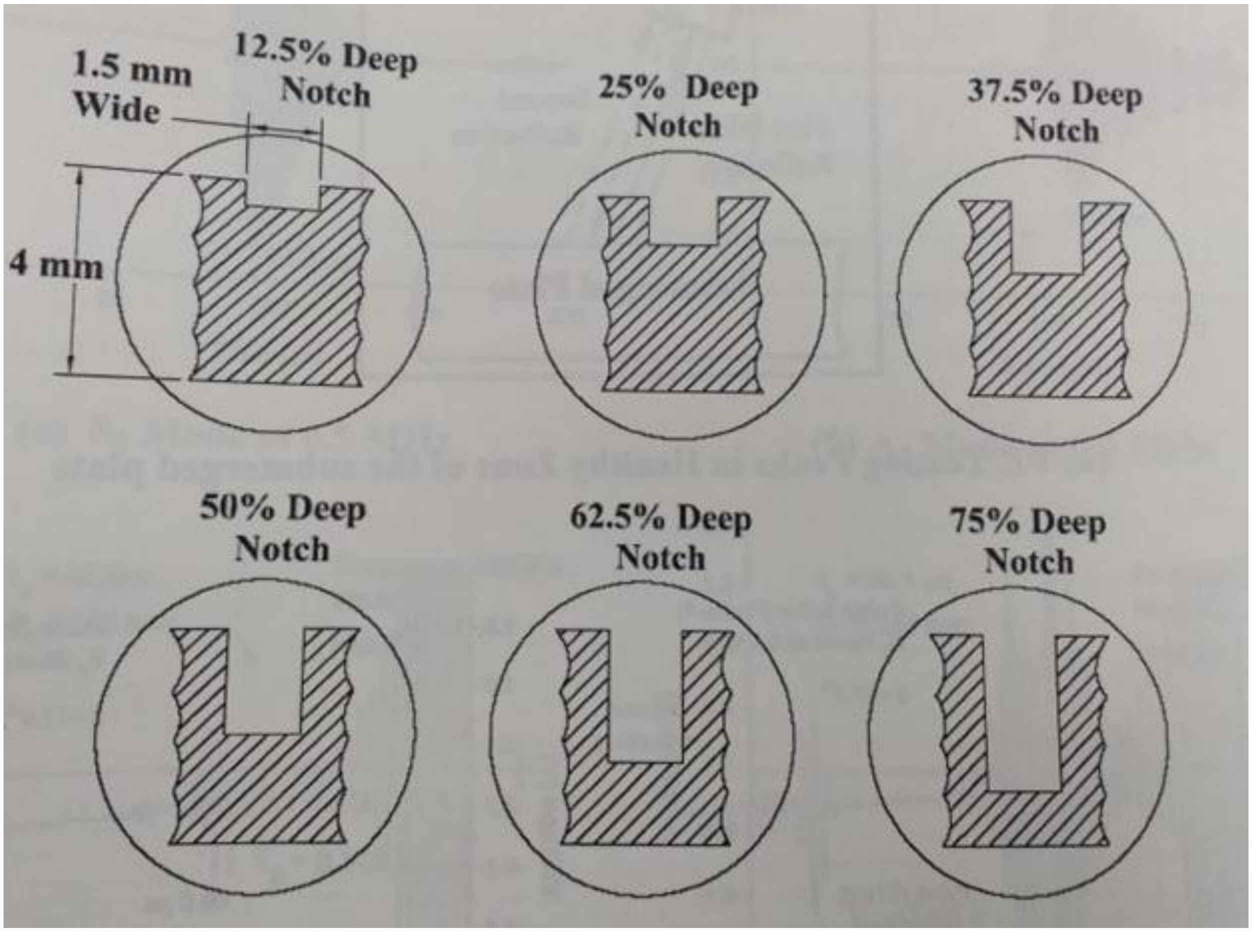
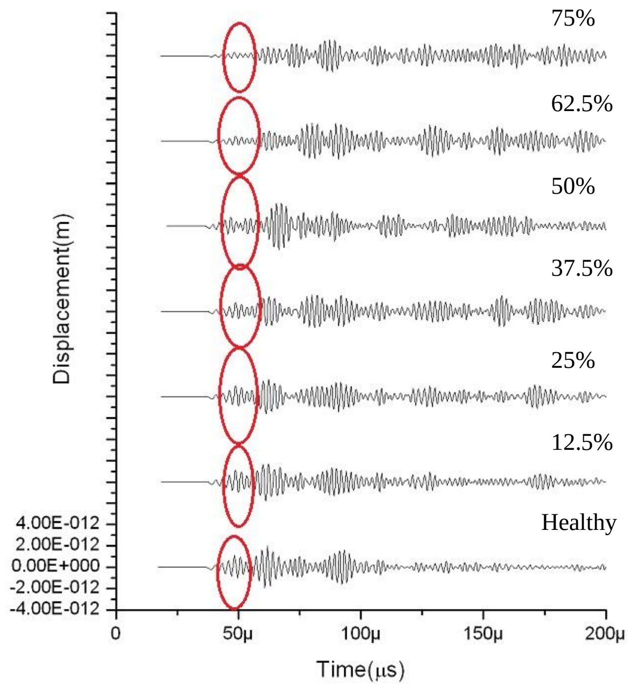


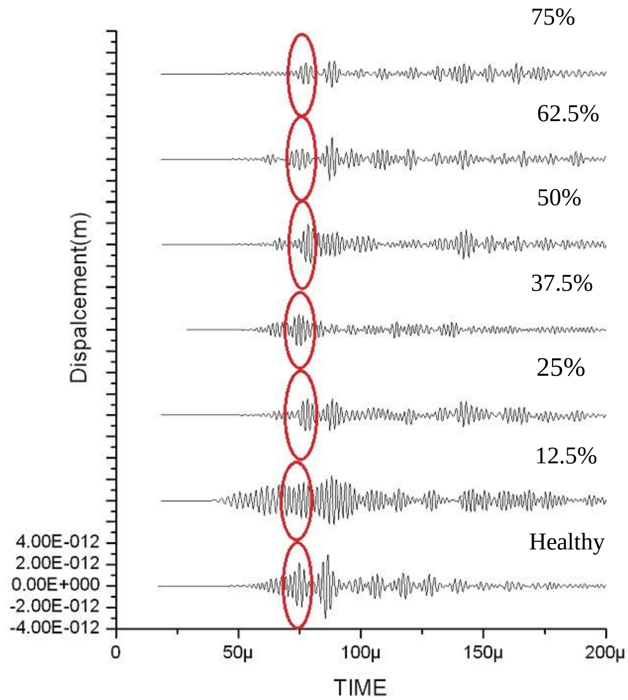
Figure 6.8: Geometry detail of Notch(1.5mm wide and depth varying from 0.5mm to 3mm with 0.5mm defect)[23].

6.7.1 Numerical and Experimental setup

A notch 1.5 mm wide has been generated in the analytical model in ANSYS at a distance 100mm from the point of excitation S as shown in the Fig. 5.11. D_P has been consistently taken as 200mm in all cases. A point R-node 200mm from S-node is selected to receive the signal. Only depth of notches has been increased with every simulation from 0.5mm to 3mm. All other conditions and parameters are kept same as defined in Section 6.2, similar to experimental conditions stated in the paper. Modification in the PT signatures are expected due to presence of flaws of varied extents in the plate. Each lamb wave mode is expected to behave differently to varying notches depth due to unique particle displacement and energy distribution across plate thickness. Fig. 6.9 and 6.10 shows the PT signatures captured using analytical model and experimentally respectively. A_1 and S_o modes has been generated analytically at .5MHz frequency. Analytical graphs are compared with experimental graph [23]. From the figure it is clear that with increase in depth of notch amplitude of the signal diminishes. It implies that with increase in depth of the notch energy is reflected back and amount of transmitted energy decreases. As anticipated earlier owing to different characteristics lamb waves will behave differently to varying notch depths.

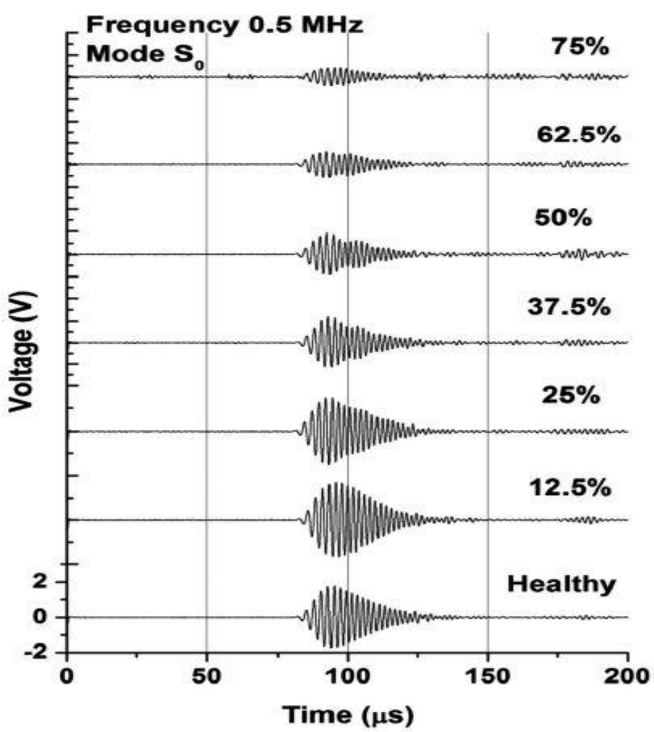


(a) S_o Mode at 0.5MHz

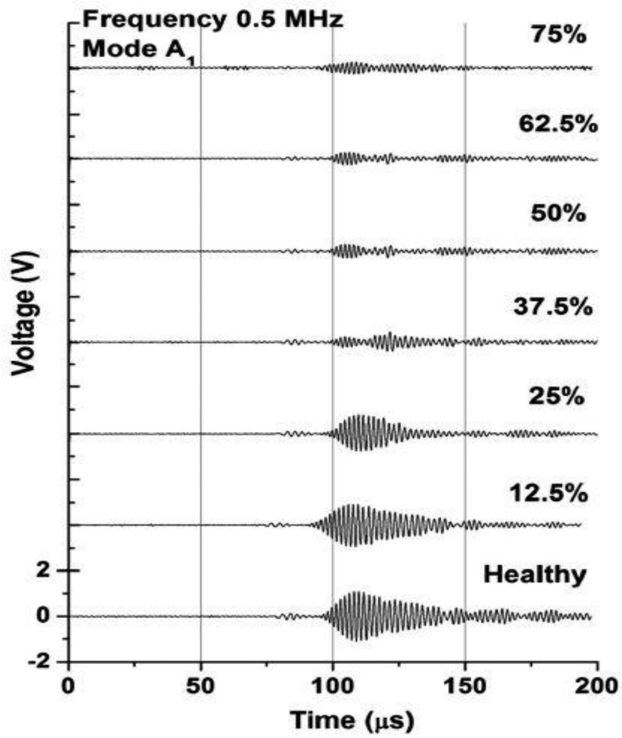


(b) A_1 Mode at 0.5MHz

Figure 6.9: Interaction of Propagating wave modes (ANSYS) with notch defects of varying depths at 0.5 MHz.



(a) S_0 mode



(b) A_1 mode

Figure 6.10: Experimental PT signatures of pulse at all notch depths at 0.5MHz [23].

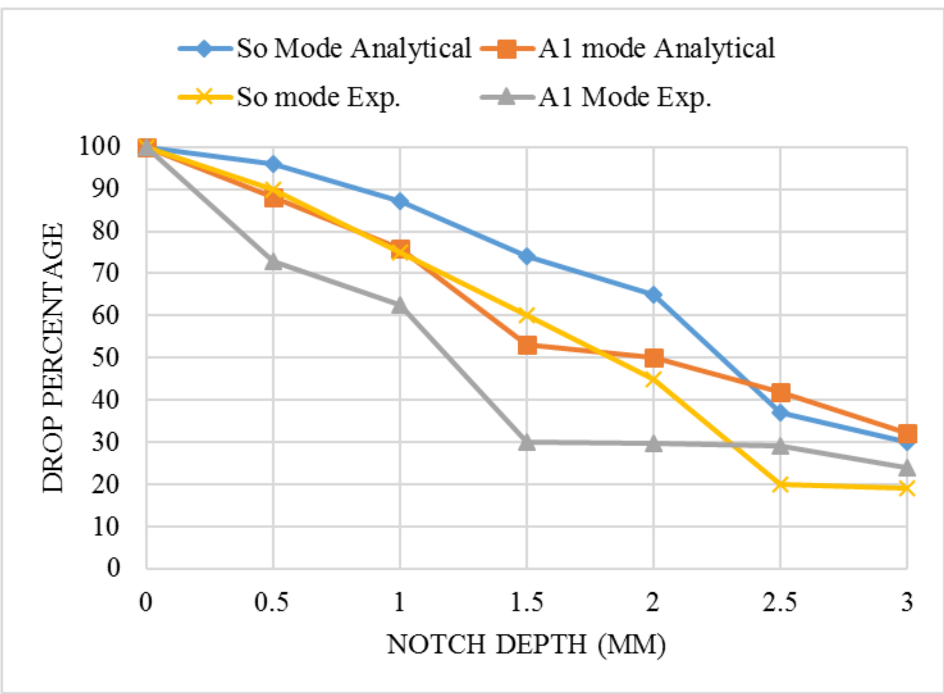


Figure 6.11: Variation in signal amplitude with varying notch depths using different Lamb wave modes at 0.5MHz in ANSYS and Experimentally.

6.7.2 Mode Sensitivity:

For the two lamb wave modes (S_o at 0.5MHz and A_1 at 0.5MHz) generated using ANSYS are further evaluated with sensitivity analysis. The value of signal without defect is taken as 100. Drop percentage in signal due to defect with respect to healthy plate signal is plotted in graph (Figure 6.10). With the presence of 0.5mm notch there is marginal drop in S_o (4%), but a bit higher drop in A_1(12%). Similar trend is followed at 1mm notch S_o losses 13% signal amplitude whereas A_1 lost 24%. But at 1.5mm defect there is potential decrease in signal amplitude in A_1, it reduced to 47%. On the other side S_o is still decreasing with same rate. Both the waves exhibits sluggish fall in the amplitude at 2mm defect.

At 2.5mm notch there is steep fall in signal amplitude of S_o mode, A_1 is consistent with pervious trend. With deeper notch sluggish fall in A_1 mode signal amplitude is recorded. In S_o mode signal drop is still consistent in this region. From the trend followed by the lamb wave it is concluded,

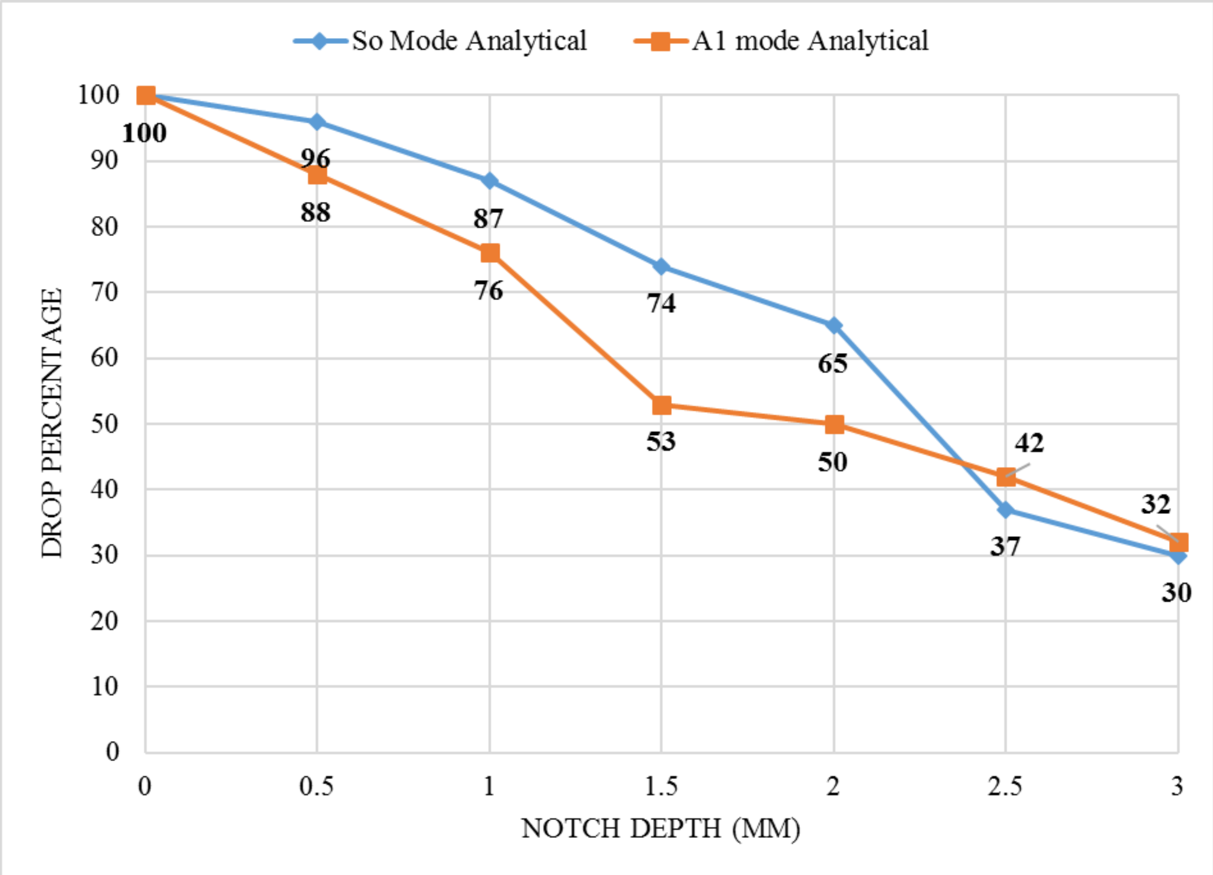
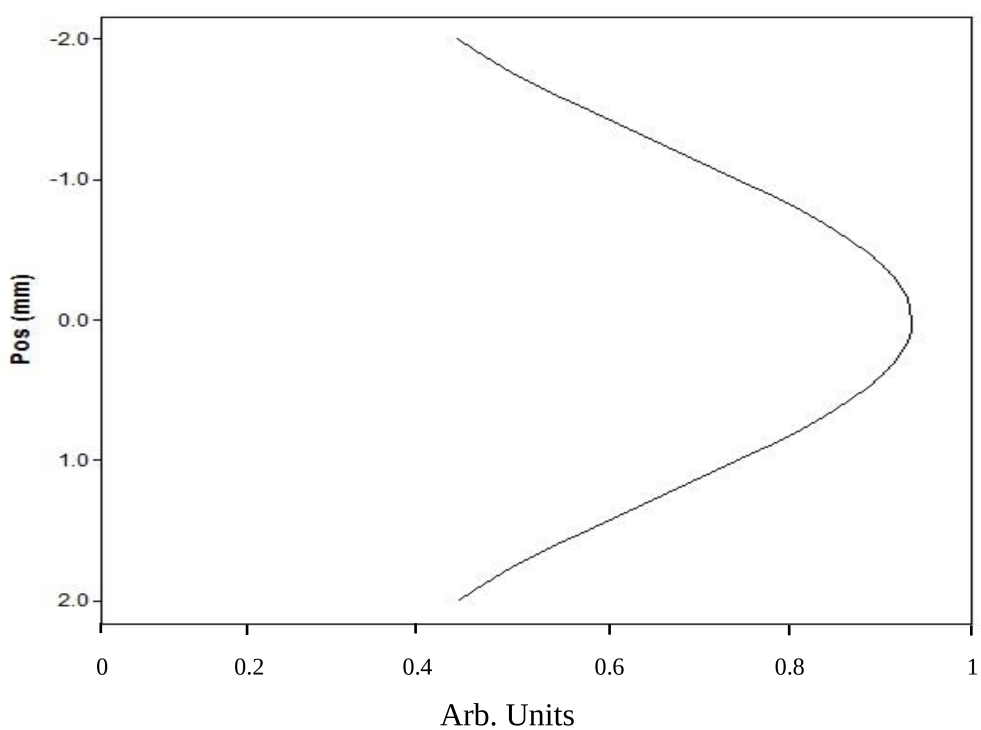


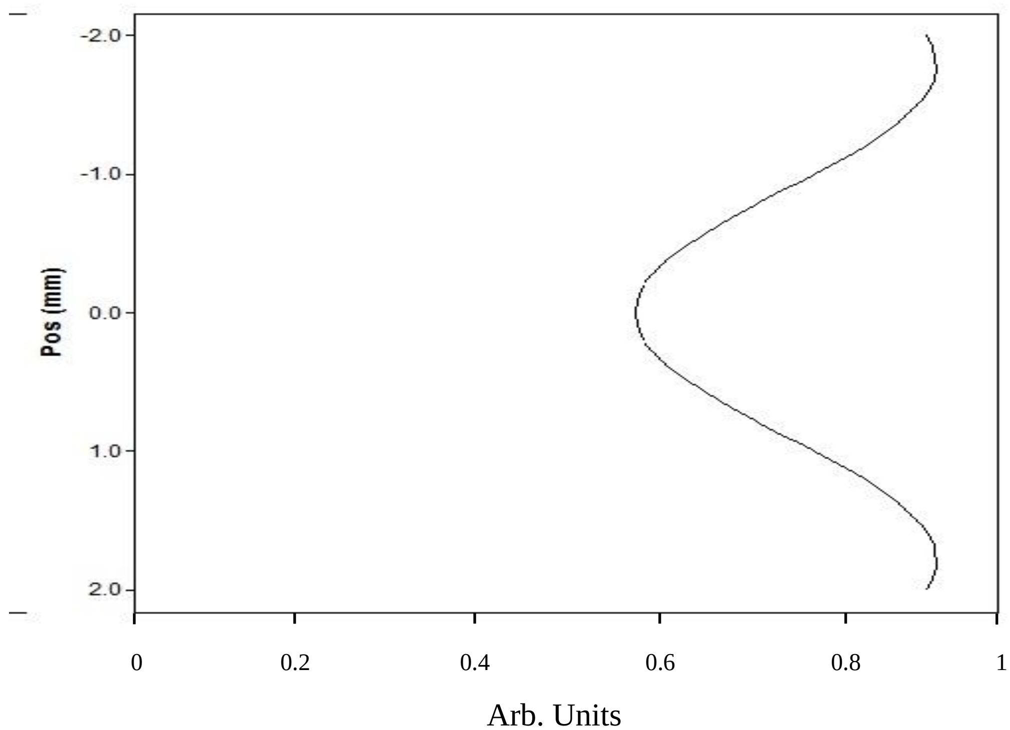
Figure 6.12: Drop in signal with notch size for selected modes at 0.5MHz.

S_o mode is sensitive to deep notches and insensitive to shallow defects. Whereas A_1 mode is sensitive to shallow defects and highly insensitive to deep defects.

This variation in the behavior of modes to notch defects can be attributed to the wave structure. From the Fig 6.11(a) it is observed that S_o mode has significant energy distribution at the core of the plate structure in comparison to surface of the plate. It is more sensitive towards deep notches. A_1 mode which shows more sensitivity to shallow notches (0.5-1mm) which to due to more energy distribution at the surface of the plates plane (Fig. 6.11 (b)).Hence this mode is more suitable to detect shallow defects in the structure. Such a mode is called as Surface sensitive mode.



(a) S_o mode at 0.5MHz



(b) A_1 mode at 0.5MHz

Figure 6.13: Wave Structure of selected Lamb wave mode.

6.8 Conclusion

In this chapter FE model of steel plate immersed in water is developed. Various characteristics of lamb wave in leaky or highly attenuative environment is studied in the modelled wave. Response of modeled lamb wave with change in propagation span, to varying defect depths etc is studied. The FE model is successfully validated with the experimental and theoretical results.

Chapter 7

Conclusions and Future scope of results

7.1 Introduction

Present work is focused on developing a Finite Element model to generate a lamb wave in a plate structure and study its behavior. Work is carried out in two steps, in the first step lamb wave is generated in the dry plate using FE technique and in the second step same methodology is applied to the plate submerged in the water. For the verification of lamb wave behavior experimental study is case of dry mode is also conducted, whereas in the case of submerged plate structure results of a publication [24] is used.

7.2 Ultrasonic Wave Propagation through Plate in air

The propagation characteristics of the lamb wave modeled in ANSYS is studying to analyze the behavior of the lamb wave generated. Various propagation characteristics like group velocity, effect of defects on wave signal amplitude, effect due to change in propagation span, mode sensitivity etc of the lamb wave is studied. For the validation of modelled results experimental testing of dry plate is also done. Major conclusions drawn from the study are summarized as:

- Different Lamb wave modes (A_o, S_o) can be generated in the FE model by changing loading patterns.
- Different lamb wave modeled in ANSYS exhibits unique propagation characteristics.
- Behavior of the modes generated in ANSYS in the presence of defects in the plate structure is similar to behavior of mode generated experimentally.
- Sensitivity analysis of modelled wave also verified the fidelity of FE technique.

7.3 Wave Propagation through Plate submerged in water

A FE model of lamb wave propagating through a steel plate submerged in water is developed here. A study about the behavior of lamb wave modelled has been carried out. Fundamental characteristics of lamb wave when the object is immersed in water are verified in the FE model.

Attenuation due to surrounding in case of submerged structure is compared with structures in dry state or air. Other characteristics like group velocity, phase velocity are also calculated. Following conclusions can be derived:

- Lamb waves can be modeled in structures immersed in water using FE technique.
- FE model can also be used as SHM tool for under water structures.

7.4 Closing Remarks

This study is a step forward and should be useful in further development of an effective monitoring technique to detect various defects like notches, cracks, dents etc in structures in dry state or in wet conditions.

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