

HEALTH MONITORING OF PLATE STRUCTURES USING ULTRASONICS

Thesis submitted in partial fulfillment of the requirements for the award of
degree of

**Master of Engineering
in
CAD/CAM AND ROBOTICS**

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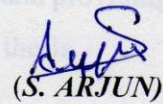


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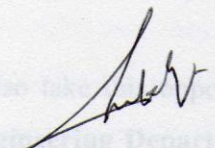
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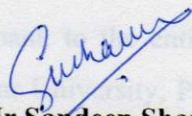
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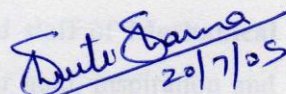
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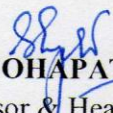
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ABSTRACT

Health monitoring for damage detection utilizing ultrasonic waves is an emerging field. It uses transmission of high frequency sound waves into a material to detect imperfections, damages or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo wherein sound is introduced into a test object and reflections (echoes) are returned to a receiver from internal imperfections. It is assisted by pulse transmission to quantify the magnitude of damages. This report presents the use of above two techniques to detect the damage in steel plates with manufactured defects in the form of holes, punches, notches.

The exact location of damage is known by pulse echo and through transmission is used to know the magnitude of damage in plates. Negative spike pulse is used as an input signal to sending transducer through Pulser/Receiver system and transmitted pulse is received at the other end by receiving transducer. Testing of plates in air is done by placing the transducer in direct contact with plate where the wave travels through the plate from the transducer with the help of couplant (ultrasonic gel). Due to some problem faced in damage detection while testing the plates in air, testing of plates is done by keeping the plate in water where the plate is surrounded by water. Ultrasonic waves are introduced at different angles in the subject specimen in both pulse echo and through transmission technique. The wave signatures obtained are analysed using digitizer card. A parametric study is carried out to see the effect of change in location of damage and magnitude of damage on wave propagation through steel plates for a particular type of damage. The final results obtained were reported in the form of voltage-time curves. For different damage types, most ideal modes were selected. Modes of different frequencies were generated and found the best mode for the testing of various defects on different plate thickness.

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1.1 Objectives of the present study

As the design and construction of Mechanical structures continue to evolve, it is becoming imperative that these structures be monitored for their health. In order to meet this need, the discipline of Structural Health Monitoring (SHM) has emerged. There are many established techniques of monitoring the health of civil and mechanical infrastructures. It involves the application of wave to structures and aims to assist engineers in realizing the full benefits of structural health monitoring. Health of several structures is monitored by recording propagation of stress waves through them. The wave characteristics change due to the deterioration in the structure and they are sensitive to the location, extent and character of damage. However, for a successful monitoring a priori knowledge of the wave characteristic due to different cases is imperative. Ultrasonics are extensively used for this purpose out of which wave propagation provides an effective solution.

The overall objectives of the present study are:

- Review of literature on propagation of ultrasonic waves through solids
- Generate and investigate the propagation of ultrasonic waves through the healthy and damaged steel specimens seeded with commonly occurring defects in plated structures.
- Characterize various damages in plates and its extent through the analysis and comparison of wave signatures of healthy and damaged steel specimens.
- To investigate the propagation of various ultrasonic guided wave modes through the damaged submerged specimens and study the fluid structure interaction with water as a couplant.
- To find the sensitivity of different types of defects with different guided wave mode to facilitate their detection.

1.2 Background

1.2.1 Structural Health Monitoring

Structural Health Monitoring (SHM) is a key development that is driving a revolution in smart-structures technologies. Promising quantum gains in the performance and cost-effective maintenance of high-value assets such as aircraft, civil infrastructure, and structural health monitoring technology will be an integral component of an increasing number of future engineering structures. The rapid advances that have been made in the past two decades in sensor technology, multifunctional materials and innovative structural concepts are now leading into the practical use of Structural Health Monitoring.

1.2.2 Techniques for SHM

Structural Health Monitoring (SHM) is estimating the state of structural health, for detecting the changes in structure that affect its performance. Two major factors that are considered in structural health monitoring are time-scale of change which deals how quickly the change occurs and Severity of change which deals the degree of change. Global technique and Local technique are two different types of techniques are available to assess the health of structure are enlisted below.

The global SHM techniques are using the dynamic characteristics of the structure to identify the damage, its approximate location and its severity, reducing the need for manual inspection. Global techniques are very attractive to civil engineers because they can be used without direct access to structural member and no previous knowledge of damage of structure is needed.

Local techniques are used most widely for assessing the health of the mechanical structures. The following are most commonly used local technique for SHM.

- **Impact Echo Method:** The impact-echo method is a technique for flaw detection in concrete. It is based on monitoring the surface motion resulting from a short-duration mechanical impact. The method overcomes many of the barriers associated with flaw detection in concrete based on ultrasonic methods. It can be used to check a tendon for prestressed grout voids but is a delicate operation requiring skilled personnel. The presence of cracks and other concrete defects as often found in

real structures influences significantly the test results and can make the evaluation impossible at times.

- **Visual and Optical Testing:** Visual inspection involves using an inspector's eyes to look for defects. The inspector may also use special tools such as magnifying glasses or mirrors gain access and more closely inspect the subject area.

- **Penetrant Testing:** Test specimens are coated with visible or fluorescent dye solution. Excess dye is then wiped out from the surface, and a developer is applied. The developer acts as blotter, drawing trapped penetrant out of imperfections open to the surface. With visible dyes, vivid colour contrasts between the penetrant and developer make "bleedout" easy to see.

- **Magnetic Particle Testing (MT):** In this method a magnetic field in a ferromagnetic material is induced and then dusting the surface with iron particles (either dry or suspended in liquid) is done. Surface and near-surface imperfections distort the magnetic field and concentrate iron particles near imperfections, previewing a visual indication of the flaw.

- **Electromagnetic Testing (ET) or Eddy Current Testing:** Eddy currents are generated in a conductive material by an induced alternating magnetic field and they flow in circles at just below the surface of the material. Interruptions in the flow of eddy currents, caused by imperfections, dimensional changes, or changes in the materials conductive and permeability properties, can be detected with the proper equipment.

- **Ultrasonic Testing (UT):** ultrasonic testing use transmission of high-frequency sound waves into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo, wherein sound is introduced into a test object and reflections (echoes) are returned to a receiver from internal imperfections or from the part's geometrical surfaces.

- **Acoustic Emission Testing (AE):** when a solid material is stressed, imperfections within the material emit short bursts of acoustic energy called "emissions." as in ultrasonic testing; acoustic emissions can be detected by special receivers. Emission sources can be evaluated through the study of their intensity, rate, and location.

- **Leak Testing (LT):** Several techniques are used to detect and locate leaks in pressure containment parts, pressure vessels, and structures. Leaks can be detected by using electronic listening devices, pressure gauge measurements, liquid and gas Penetrant techniques, and/or a simple soap-bubble test. Wave propagation provides an efficient means of characterizing defects in structures. For this purpose it is necessary to analyze scattering of waves by such defects. The sudden occurrence of small flaws initiated from damage sites in structural solids generates elastic waves that carry important information on the nature of damage.

Out of all these technique, ultrasonic testing is chosen as the best testing technique for testing of plated structures.

1.3 Ultrasonics for Health Monitoring

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more.

Figure 1.1 gives information about setup of ultrasonic testing in flaw detection.

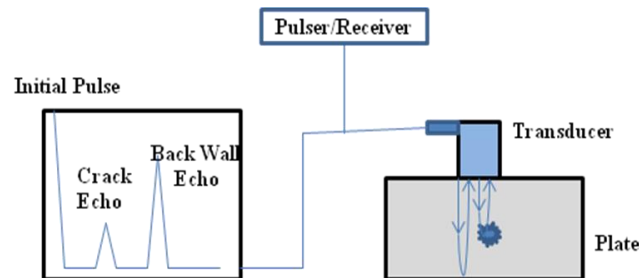


Figure 1.1: Ultrasonic testing

A typical UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices. A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. This is how defect is detected from the time of flight of received signal (t) and knowing the velocity (v) of wave in a particular solid medium, the defect can be located as

$$D = \frac{vt}{2} \quad - (1.1)$$

This is called pulse echo technique. It is assisted by through transmission in which two transducer are used for testing the object specimen. The magnitude of damage is found from the change in amplitude of the through transmission signal.

1.4 Organization of Work

This thesis explains the Ultrasonic wave for damage detection in plates. Chapter 1 gives a background of Structural health monitoring using various Non destructive techniques and establishes ultrasonics as a potential solution for damage detection in plate structures.

Chapter 2 gives in details about the ultrasonic waves used as testing technique for detecting damage detection, different modes of wave propagation and its applications, characteristics of ultrasonic beam and details of experimental setup needed.

Chapter 3 discusses the various analytical works using ultrasonics in plate structures.

Chapter 4 discusses in detail about experimental setup used for the study and various results obtained.

Chapter 5 discusses about the testing methodology and results of plates in water. Selection of lamb wave modes for testing of different plate thickness, different defects and scanning of plates is employed.

2.1 Introduction

Ultrasonic nondestructive testing introduces high frequency sound waves into a test object to obtain information about the object without altering or damaging it in any way. It is used for detection of damage in structures. This is one of the best non destructive testing methods where ultrasonic wave is send into the structure to find the location and magnitude of the defect. Ultrasonic wave propagation varies with change in the medium in which the wave propagates.

2.2 Modes of Wave Propagation

The ultrasonic waves propagate in a number of ways in a medium. Wave propagation depends on material properties of the structure. On the basis of the mode of particle displacement, these waves can be classified 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
5. Creeping or Head waves

Out of these longitudinal and transverse wave propagations are most important and are extensively used in ultrasonic NDT applications.

2.2.1 Longitudinal or Compressional waves

In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation as shown in the Figure 2.1. Since compressional and dilational forces are active in these waves, they are also called pressure or compressional waves. They are also sometimes called density waves because their particle density fluctuates as they move. Compression waves can be generated in liquids, as well as solids because the energy travels through the atomic structure by a series of compression and expansion (rarefaction) movements.

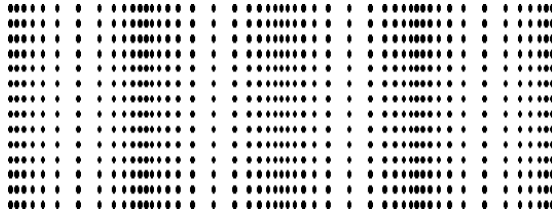


Figure 2.1: Longitudinal or Compressional waves

2.2.2 Transverse or Shear wave

In the transverse or shear wave, the particles oscillate at a right angle or transverse to the direction of propagation as shown in the Figure 2.2. Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves. In fact, shear waves are usually generated in materials using some of the energy from longitudinal waves.

For the propagation of transverse waves, it is necessary that each particle exhibits a strong force of attraction to its neighbours, so that as a particle moves back and forth it pulls its neighbour with it. Due to this reason air and water do not support transverse waves. In gases, the forces of attraction between molecules are so small that shear waves cannot be transmitted. The same is true of a liquid, unless it is particularly viscous or is present as a very thin layer. The velocity of transverse waves is approximately 50% of the longitudinal wave velocity for the same material.



Figure 2.2: Transverse or Shear wave

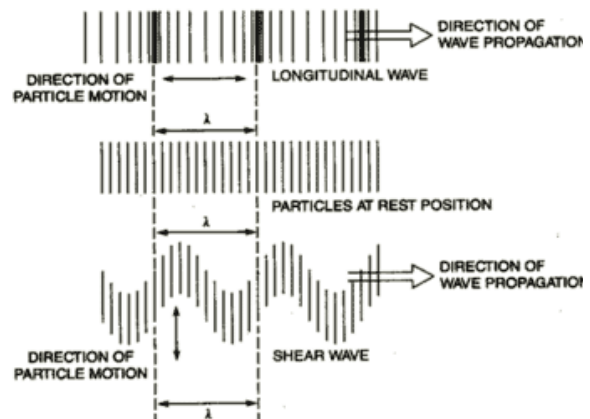


Figure 2.3: Longitudinal and Transverse wave

The particle movement responsible for the propagation of longitudinal and shear waves is illustrated in the Figure 2.3.

2.2.3 Surface (or Rayleigh) waves

Surface (or Rayleigh) waves travel on the surface of a relatively thick solid material penetrating to a depth of one wavelength. The particle movement has an elliptical orbit as shown in the Figure 2.4. The major axis of ellipse is perpendicular to the surface along which the waves are travelling. Rayleigh waves are useful because they are very sensitive to surface defects and they follow the surface around curves. These waves can travel along the flat and curved surfaces. These waves are subjected to less attenuation in a given material than the longitudinal or transverse waves. Because of this, Rayleigh waves can be used to inspect areas that other waves might have difficulty reaching.

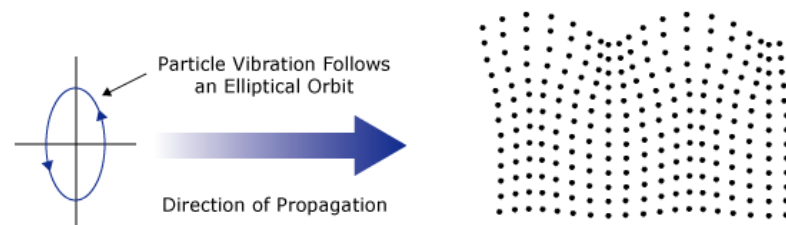


Figure 2.4: Surface (or Rayleigh) waves

2.2.4 Lamb waves

Plate or Lamb waves can be propagated only in very thin metals. Lamb waves are the most commonly used plate waves in NDT. Lamb waves are complex vibrational waves that travel through the entire thickness of a material. Propagation of lamb waves depends on the density and the elastic material properties of a component. They are also influenced a great deal by the test frequency and material thickness.

With lamb waves, a number of modes of particle vibration are possible, but the two most common are symmetrical and asymmetrical as shown in the Figure 2.5. The complex motion of the particles is similar to the elliptical orbits for surface waves. Symmetrical lamb waves move in a symmetrical fashion about the median plane of the plate. This is sometimes called the extensional mode because the wave is “stretching and compressing” the plate in the wave motion direction. Wave motion in the symmetrical mode is most efficiently produced when the exciting force is parallel to the plate. The asymmetrical lamb wave mode is often called the “flexural mode” because a large portion of the motion moves in a normal direction to the plate, and a

little motion occurs in the direction parallel to the plate. In this mode, the body of the plate bends as the two surfaces move in the same direction.

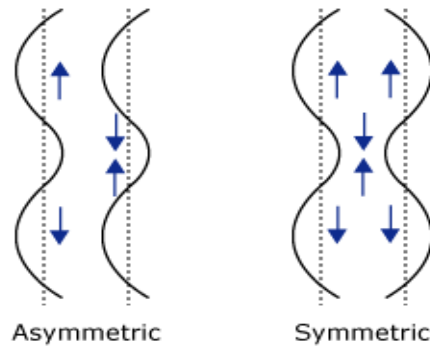


Figure 2.5: Lamb waves

2.2.5 Creeping waves

These waves are also called head waves. The behavior of creeping waves is similar to that of longitudinal waves. They travel as fast as longitudinal waves and the creeping waves should not be misunderstood as moving slowly. These are generated parallel to scanning surface, enabling detection of surface breaking defects. These have limited range and as these travel just below the surface and not on the surface, so the couplant has no influence.

Lamb waves are most preferred waves for the ultrasonic testing in damage detection in steel plates, since the lamb waves propagates only in very thin metals. Symmetric lamb waves are used to find the damage in normal plates whereas antisymmetric lamb waves are used to find the damage in plates with the bend.

2.3 Characteristics of Beam

Ultrasonic waves are generated by exciting piezo electric transducer at very high frequencies about 20KHz. The characteristics of beam profile are discussed.

2.3.1 Beam Profile

The sound that emanates from a piezoelectric transducer does not originate from a point, but instead originates from most of the surface of the piezoelectric element. The acoustic pressure in the path of an acoustic beam is measured, it can be seen that it varies with distance and two distinct zones can be found as in the case in optics. These zones are known as:

- 1 Near field or Fresnel Zone
- 2 Far field or Fraunhofer Zone

The length of these zones depends on parameters like ultrasonic frequency and diameter of the transducer.

2.3.1.1 Near field

It is the region in an ultrasonic beam in front of the transducer face which is subjected to large variation of intensity. In the near field, components of the ultrasonic wave from different portions of the crystal will constructively and destructively interact to produce pressure maxima and minima. For non-focused source, it is the zone of the ultrasonic beam extends from the crystal face to the near field last pressure maximum of the beam along the beam axis. The region in which these maxima and minima occur is known as the ‘Near Field’ of the sound beam. The length of near beam (N) is determined by the size of the active element (diameter D) and the wavelength of the ultrasonic wave from the relation.

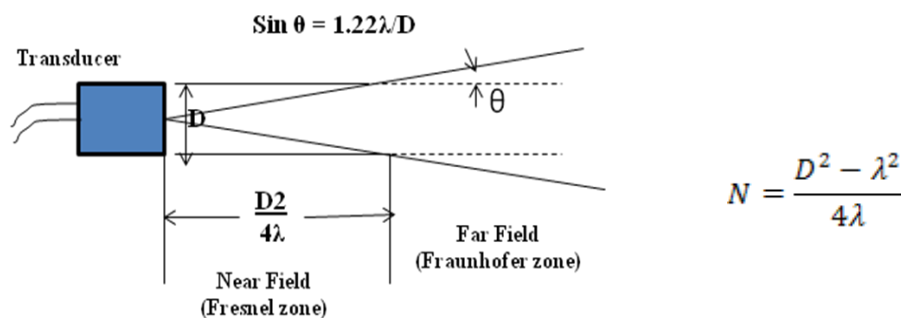


Figure 2.6: Beam Profile

2.3.1.2 Far field

The region beyond distance N of ultrasonic beam path, that extends away from the last pressure maximum along the beam axis, is known as far field or Fraunhofer region of the ultrasonic beam. In this region no interference effects exist. The only effect of consequence is the spreading of ultrasonic beam. In the far field the amplitude of the ultrasonic wave decreases with distance due to beam spreading and attenuation. In this region the inverse law is applicable. In other words the intensity is inversely proportional to the square of the distance.

2.3.2 Reflection, Refraction and 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 hits an interface at an angle, some of the energy can cause particle movement in the transverse direction to start a shear (transverse) wave. Mode conversion occurs when a wave encounters an interface between materials of different acoustic impedances and the incident angle is not normal to the interface.

When sound waves pass through an interface between materials having different acoustic velocities, refraction takes place at the interface. The larger the difference in acoustic velocities between the two materials, the more the sound is refracted. Notice that the shear wave is not refracted as much as the longitudinal wave. This occurs because shear waves travel slower than longitudinal waves. Therefore, the velocity difference between the incident longitudinal wave and the shear wave is not as great as longitudinal waves but it is between the incident and refracted longitudinal waves. Also note that when a longitudinal wave is reflected inside the material, the reflected shear wave is reflected at a smaller angle than the reflected longitudinal wave. This is also due to the fact that the shear velocity is less than the longitudinal velocity within a given material. Snell's Law holds true for shear waves as well as longitudinal waves and can be written as follows.

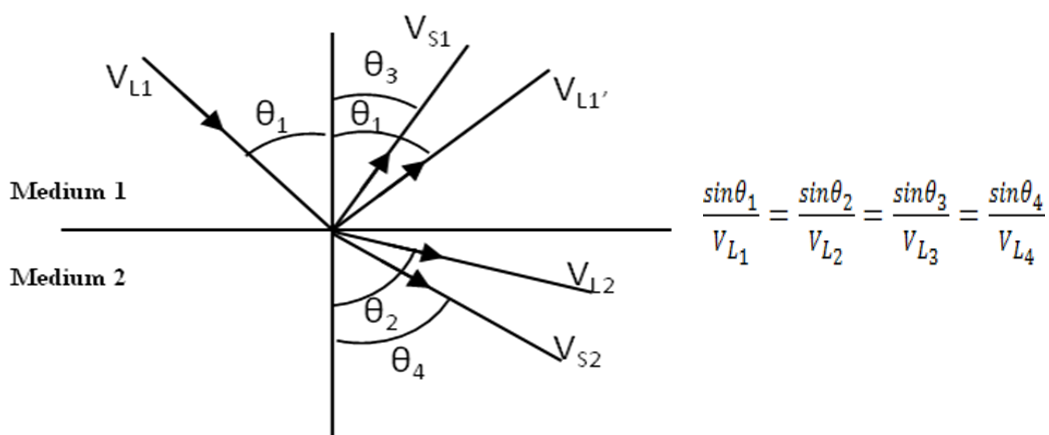


Figure 2.7: Snell's Law

Where:

V_{L1} - is the longitudinal wave velocity in material 1.

V_{L2} - is the longitudinal wave velocity in material 2.

V_{S1} - is the shear wave velocity in material 1.

V_{S2} - is the shear wave velocity in material 2.

2.3.3 Critical Angle

For small angles of incidence sound waves travelling at an angle from medium 1 give rise to the longitudinal as well as shear waves, in the medium 2. Such a situation is very confusing for NDT inspection, as both of these waves present in the medium 2, travel at different velocities and give rise to separate on the flaw detector screen.

As a solution to this problem the longitudinal wave is not allowed to enter the test piece and is eliminated by total internal reflection. Therefore, a clear knowledge about the formation of critical angles becomes important, especially in the case of designing of angle beam transducers.

2.3.3.1 First Critical Angle

If the angle of incidence A is increased in the particular case when $c_2 > c_1$, angle B of the refraction longitudinal wave also increases till, for some specific value of angle A , the angle B becomes equal to 90° . At this angle (A_1) there would be no refraction longitudinal wave in the medium 2 and only the shear wave would be propagating. This value of angle A is called First Critical Angle (A_1).

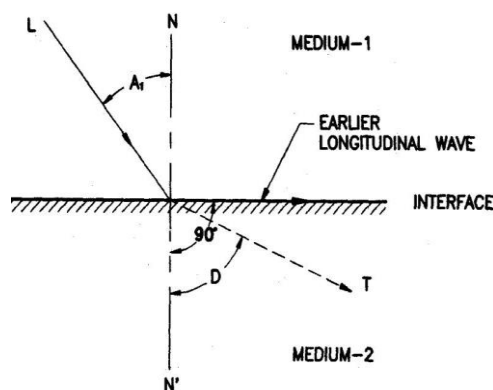


Figure 2.8: First Critical Angle

Generally, the angle beyond the first critical angle is used for ultrasonic inspection at oblique incidence. Taking the refracted angle B for longitudinal wave as 90° the Snell's equation can be written as

$$\frac{\sin A_1}{c_1} = \frac{\sin 90}{c_2(\text{long})}$$

or

$$A_1 = \text{Sin}^{-1} \left(\frac{c_1}{c_2} \right)$$

Where c_1 and c_2 are longitudinal velocities in the two media.

2.3.2.2 Second Critical Angle

If the angle of incidence A is further increased beyond A_1 , a situation would arrive, when angle D of the refracted shear wave would be equal to 90° . The value of angle A is now known as second critical Angle (A_2). At this position the Snell's equation can be written as

$$\frac{\sin A_2}{c_1(\text{long})} = \frac{\sin 90}{c_2(\text{trans})}$$

$$A_2 = \text{Sin}^{-1} \left(\frac{c_1(\text{long})}{c_2(\text{long})} \right)$$

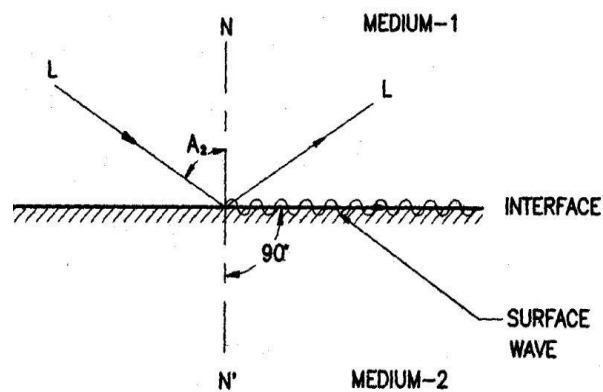


Figure 2.9: Second Critical

The Figure 2.9 shows the formation of Second critical angle. At this position there would be no sound beam entering the medium 2 and the shear wave would appear as surface wave.

2.4 Terminology for Ultrasonic wave propagation

Ultrasonic waves are simply organized mechanical vibrations traveling through a medium, which may be a solid, a liquid, or a gas. These waves will travel through a given medium at a specific speed or velocity, in a predictable direction, and when they encounter a boundary with a different medium they will be reflected or transmitted according to simple rules. This is the principle of physics that underlies ultrasonic flaw detection.

- 1. Frequency:** All sound waves oscillate at a specific frequency, or number of vibrations or cycles per second, which we experience as pitch in the familiar range of audible sound. Human hearing extends to a maximum frequency of about 20,000 cycles per second (20 KHz), while the majority of ultrasonic flaw detection applications utilize frequencies between 500 KHz to 10 MHz. At frequencies in the Megahertz range, sound energy does not travel efficiently through air or other gasses, but it travels freely through most liquids and common engineering materials.
- 2. Wave Speed:** The speed of a sound wave varies depending on the medium through which it is traveling, affected by the medium's density and elastic properties. Different types of sound waves will travel at different velocities.
- 3. Wavelength of a Wave:** Wavelength is related to frequency and velocity by the simple equation Wavelength (λ) =velocity (V)/frequency (f). In ultrasonic flaw detection, the generally accepted lower limit of detection for a small flaw is one-half wavelength, and anything smaller than that will be invisible. In ultrasonic thickness gauging, the theoretical minimum measurable thickness is one wavelength.
- 4. Acoustic impedance:** Sound travels through materials under the influence of sound pressure. Because molecules or atoms of a solid are bound elastically to one another, the excess pressure results in a wave propagating through the solid. The **Acoustic impedance (Z)** of a material is defined as the product of its density (ρ) and acoustic velocity (V).

$$z = \rho V$$

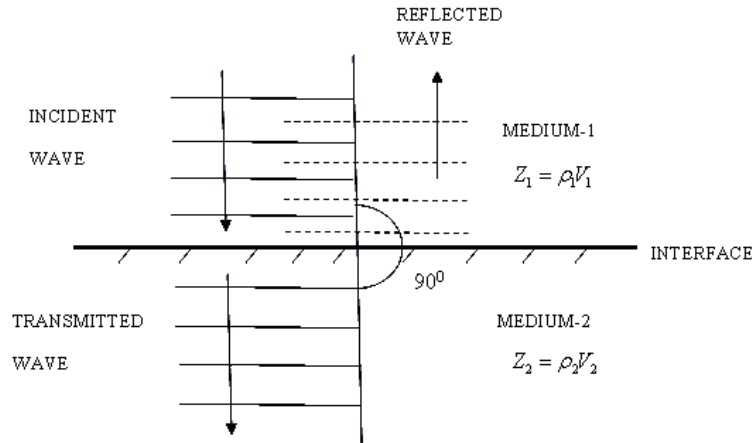


Figure 2.10: Reflection and Transmission of sound wave at normal incidence

$$\text{Reflection coefficient, } R = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1} \right] = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

$$\text{Transmission coefficient, } T = \frac{2Z_2}{Z_2 + Z_1} = \frac{2\rho_2 V_2}{\rho_2 V_2 + \rho_1 V_1}$$

5 Reflection and transmission coefficients (pressure) Ultrasonic waves are reflected at boundaries where there is a difference in acoustic impedances (Z) of the materials on each side of the boundary as shown in the Figure 2.10. This difference in Z is commonly referred to as the impedance mismatch. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the interface or boundary between one medium and another.

The fraction of the incident wave intensity that is refracted can be derived because particle velocity and local particle pressures must be continuous across the boundary. When the acoustic impedances of the materials on both sides of the boundary are known, the fraction of the incident wave intensity that is reflected can be calculated with the equation below. The value produced is known as the reflection coefficient. Multiplying the reflection coefficient by 100 yields the amount of energy reflected as a percentage of the original energy.

$$R = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1} \right]^2$$

Since the amount of reflected energy plus the transmitted energy must equal the total amount of incident energy, the transmission coefficient is calculated by simply subtracting the reflection coefficient from one.

2.5 Ultrasonic Testing techniques

Ultrasonic energy striking at an interface of two different materials, either at normal or at inclined incidence, is partially reflected back or partially transmitted into the other medium. It is the transmitted part of energy which is utilized in inspection work. Depending on conditions of test and information required, a number of techniques are used for the ultrasonic inspection. Various techniques of ultrasonic most commonly used are:

1. **Pulse echo method**
2. **Through transmission method**
3. **Two transducer method**
4. **Resonance method**

2.5.1 Pulse Echo Method

In the pulse-echo method, a piezoelectric transducer with its longitudinal axis located perpendicular to and mounted on or near the surface of the test material is used to transmit and receive ultrasonic energy. The ultrasonic waves are reflected by the opposite face of the material or by discontinuities, layers, voids, or inclusions in the material, and received by the same transducer, where the reflected energy is converted into an electrical signal as shown in the Figure 2.11. The electrical signal is computer processed for display on a video monitor or TV screen. The display can show the relative thickness of the material, depth into the material where flaws are located, and (with proper scanning hardware and software), where the flaws are located in the X-Y plane.

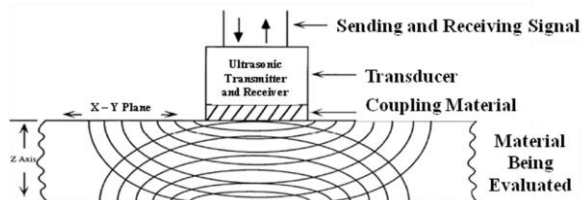


Figure 2.11: Principle of Pulse Echo method of inspection

2.5.2 Through Transmission Method

In the through-transmission method, an ultrasonic transmitter is used on one side of the material while a detector is placed on the opposite side as shown in the Figure 2.12. One unit acts as transmitter and the other unit as receiver. The beam from the transmitter T travels through the material to its opposite surface where the receiving transducer R is placed. Scanning of the material using this method will result in the location of defects, flaws, and inclusions in the X-Y plane.

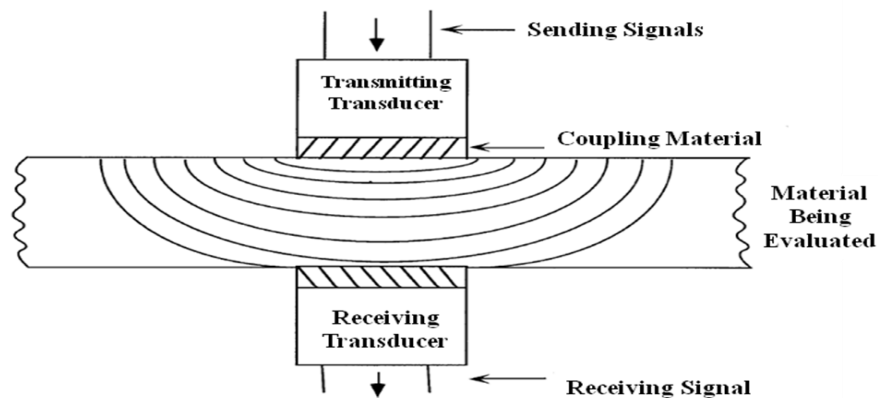


Figure 2.12: Principle of through transmission of ultrasonic testing

2.5.3 Two Transducer 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 in to 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. These transducers are popularly known as ‘twin’ or T-R probes.

2.5.4 Resonance Method

The method uses resonance phenomenon to measure the material thickness or to determine the quality of bonding in two materials. In a situation that the thickness of the material equals half the wavelength of the sound or it’s multiple, resonance takes

place. The frequency of the continuous longitudinal waves transmitted in the material is varied till standing waves are set up in the material.

Presence of resonance is indicated by an increase in amplitude as the probe is moved and a change of resonant frequency is seen, which cannot be accounted for by a change in material thickness, if any, it is usually an indication of discontinuity.

From the above methods, Pulse Echo method is mostly used in Ultrasonic testing to find location of defect in specimen and Through Transmission is mostly used in testing using ultrasonics to find the magnitude of the defect in Specimen.

2.6 Transducer (probe) and its Characteristics

The transducer is a very important part of the ultrasonic instrumentation system. The transducer incorporates a piezoelectric element, which converts electrical signals into mechanical vibrations (transmit mode) and mechanical vibrations into electrical signals (receive mode). Many factors, including material, mechanical and electrical construction, and the external mechanical and electrical load conditions, influence the behavior of a transducer.

The Figure 2.13 shown tells about the inner parts of transducer.

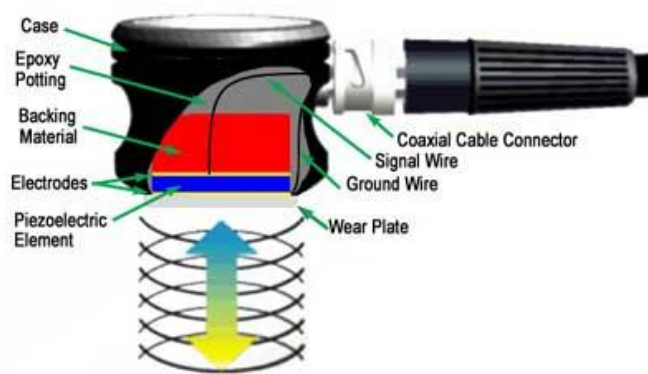


Figure 2.13: Transducer

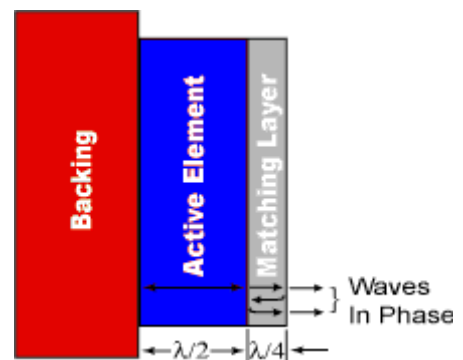


Figure 2.14: Components of Transducer

An ultrasonic transducer itself is a device that is capable of generating and receiving ultrasonic vibrations. An ultrasonic transducer is made up of an active element, a backing, and wears plate. The active element is a piezoelectric or single crystal

material which converts electrical energy to ultrasonic energy. It will also then receives back ultrasonic energy and converts it to electrical energy. The electrical energy pulse is generated from an instrument such as a flaw detector.

Main components of Transducer/Probe head as shown in Figure 2.15 are,

1. Active element
2. Backing material
3. Matching layer

The backing is most commonly a highly attenuative and very dense material and is used to control the vibration of the transducer crystal by absorbing the energy that radiates from the back face of the piezoelectric element. When the acoustic impedance of the backing material matches that of the piezoelectric crystal, the result is a highly damped transducer with excellent resolution. By varying the backing material in order to vary the difference in impedance between the backing and the piezoelectric crystal, a transducer will suffer somewhat and resolution may be much higher in signal amplitude or sensitivity.

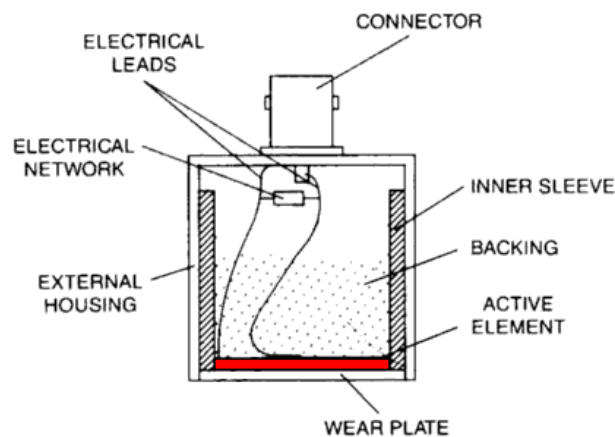


Figure 2.15: Components of Transducer

The main purpose of the wear plate is simply to protect the piezoelectric transducer element from the environment. Wear plates are selected to generally protect against wear and corrosion. In an immersion-type transducer, the wear plate also serves as an acoustic transformer between the piezoelectric transducer element and water, wedge or delay line.

The backing material supporting the crystal has a great influence on the damping characteristics of a transducer. Using a backing material with impedance similar to

that of the active element will produce the most effective damping. Such a transducer will have a narrow bandwidth resulting in higher sensitivity. As the mismatch in impedance between the active element and the backing material increases, material penetration increases but transducer sensitivity is reduced.

2.6.1 Transducer characteristics

1. **Sensitivity:** sensitivity of the probe head and flaw detection system is its ability to detect the smallest possible defects. It is a measure to produce a discriminable indication from the smallest flaw on the screen of the flaw detector system. It refers to the amplitude of the electrical voltage generated by the probe, depending upon the magnitude of the reflected ultrasonic signal impinging on its surface. Therefore, sensitivity of a transducer is its capability to detect the smallest flaw.
2. **Resolution:** it is the ability of an ultrasonic transducer to separate echoes from two or more defects located close together in depth. Heavy damping on the active element produces short length, wide bandwidth ($f_2 - f_1$) pulse with low mechanical q , giving high resolution.

f_0 = central resonant frequency

f_1, f_2 = frequencies where the amplitude is 70% of its value at f_0

Mechanical quality factor, $q = f_0 / (f_2 - f_1)$.

Damping coefficient, $b = a_0/a_1 = a_1/a_2$.

With heavy damping, the time required for the transducer to stop vibrating after receiving a large high voltage pulse decreases. If the damping is low, the pulse is long which has a poor resolving power.

- 3 **Dead zone:** the crystal of the probe energized by short electrical pulses of a particular pulse duration and pulse repetition frequency. When the probe is acting as a transmitter and receiver, the transmission continuous until the pulse dies out and then only it can act as the receiver. By the time the pulse dies out, the sonic energy travels into the material and the distance travelled by the sound energy within the pulse duration period is known as 'dead zone'. When

a flaw lies within this zone, signal from this will not be received and hence, cannot be detected. To minimize dead zone, short pulses can be used and a delay block (or water column in immersion testing) can be brought in front of the probe.

2.7 Methods of Data Presentation

Ultrasonic data can be collected and displayed in a number of different formats. The three most common formats are known in the NDT world as **A-scan**, **B-scan** and **C-scan** presentations. Each presentation mode provides a different way of looking at and evaluating the region of material being inspected. Modern computerized ultrasonic scanning systems can display data in all three presentation forms simultaneously.

2.7.1 A-scan presentation

The **A-scan** presentation displays the amount of received ultrasonic energy as a function of time. The relative amount of received energy is plotted along the vertical axis and the elapsed time (which may be related to the sound energy travel time within the material) is displayed along the horizontal axis. Most instruments with an a-scan display allow the signal to be displayed in its natural radio frequency form (*rf*), as a fully rectified *rf* signal, or as either the positive or negative half of the *rf* signal. In the **A-scan** presentation, relative discontinuity size can be estimated by comparing the signal amplitude obtained from an unknown reflector to that from a known reflector. Reflector depth can be determined by the position of the signal on the horizontal sweep.

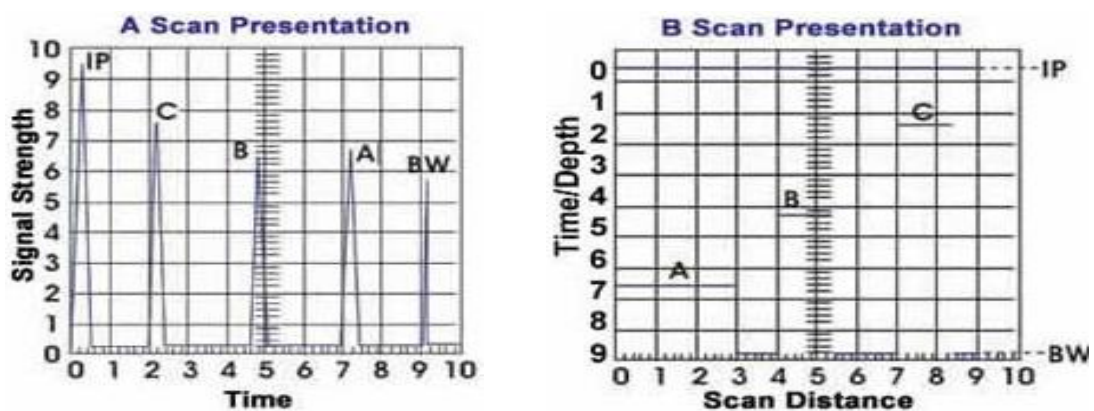


Figure 2.16: (a) A Scan Presentation, (b) B Scan Presentation

In the illustration of the **A-scan** presentation to the right, the initial pulse generated by the transducer is represented by the signal **ip**, which is near time zero. As the transducer is scanned along the surface of the part, four other signals are likely to appear at different times on the screen. When the transducer is in its far left position, only the **ip** signal and signal **a**, the sound energy reflecting from surface **a**, will be seen on the trace. As the transducer is scanned to the right, a signal from the back wall **bw** will appear later in time, showing that the sound has travelled farther to reach this surface. When the transducer is over flaw **b**, signal **b** will appear at a point on the time scale that is approximately halfway between the **ip** signal and the **bw** signal. Since the **ip** signal corresponds to the front surface of the material, this indicates that flaw **b** is about halfway between the front and back surfaces of the sample. When the transducer is moved over flaw **c**, signal **c** will appear earlier in time since the sound travel path is shorter and signal **b** will disappear since sound will no longer be reflecting from it.

2.7.2 B-scan presentation

The B-scan presentation is a profile (cross-sectional) view of the test specimen. In the B-scan, the time-of-flight (travel time) of the sound energy is displayed along the vertical axis and the linear position of the transducer is displayed along the horizontal axis. From the b-scan, the depth of the reflector and its approximate linear dimensions in the scan direction can be determined. The b-scan is typically produced by establishing a trigger gate on the a-scan. Whenever the signal intensity is great enough to trigger the gate, a point is produced on the b-scan. The gate is triggered by the sound reflecting from the back wall of the specimen and by smaller reflectors within the material. In the b-scan image above, line **a** is produced as the transducer is scanned over the reduced thickness portion of the specimen. When the transducer moves to the right of this section, the back wall line **bw** is produced. When the transducer is over flaws **b** and **c**, lines that are similar to the length of the flaws and at similar depths within the material are drawn on the b-scan. It should be noted that a limitation to this display technique is that reflectors may be masked by larger reflectors near the surface.

2.7.3 C-scan presentation

The c-scan presentation provides a plan-type view of the location and size of test specimen features. The plane of the image is parallel to the scan pattern of the transducer. C-scan presentations are produced with an automated data acquisition system, such as a computer controlled immersion scanning system. Typically, a data collection gate is established on the a-scan and the amplitude or the time-of-flight of the signal is recorded at regular intervals as the transducer is scanned over the test piece. The relative signal amplitude or the time-of-flight is displayed as a shade of grey or a colour for each of the positions where data was recorded. The c-scan presentation provides an image of the features that reflect and scatter the sound within and on the surfaces of the test piece.

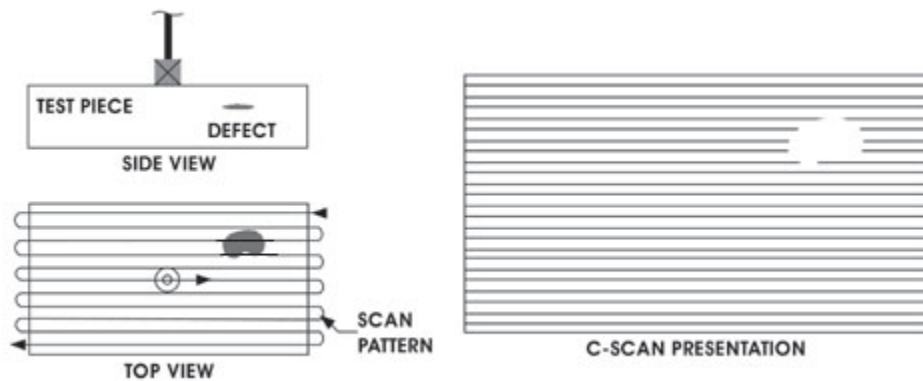


Figure 2.17: C-scan presentation

2.8 Probe Selection

The selection of probe suitable for a particular job is an important step before starting the work. The probe must comply with the conditions dictated by the material of the work piece, its shape and the test information requirements. This is naturally only possible provided that the basics of acoustics allow it.

2.8.1 Size of the Probe

The size or diameter of the active element has its own significance. Generally it is not considered important that a choice of diameter would also be helpful in several situations, a probe of any available diameter is accepted and used for the inspection.

A number of parameters are dependent on the diameter, *e.g.*, near zone and beam profile etc. due to limitation of mode of vibration of the piezoelectric disc. It is always possible to choose any diameter for any desired frequency.

2.8.2 Contour Matching Soles

In the case of using contact method for the inspection of pipes, rods etc. having small diameter, the contact area between the job and probe can be very small. According to Bureau of Indian Standards, it is recommended that wherever the surface is curved and the curvature is of regular nature having a minimum radius of 225mm, it may be tested with flat face probe. If the surface is extremely smooth, standard flat face probe may be used on convex surface with a minimum radius of 50 mm and where it is concave with a minimum radius 300mm, flat face probe may be used.

In all such cases the contact is not good resulting in heavy loss of energy. A small amount of sound energy is transmitted into the job. In such case it is helpful if the contact area is increased by providing the probe with a sole having a curvature matching with the curvature of the job. This plano-concave sole can either be cylindrical or spherical depending on the job to be inspected. Such soles can be provided in the case of normal or angle beam probe.

2.8.3 Frequency

Frequency of probe plays an important role as it affects its testing capability in several ways. In practice, it is seen that in several situations the requirements are conflicting and a compromise is to be made between favourable and adverse effects to achieve the best possible choice of frequency. Sensitivity, resolution, penetration and beam spread are largely dependent of the probe and can be modified to an extent by changes in other parameters.

Frequency selection requirements are: (i) penetration and (ii) detectability of small flaws. Sound propagation in a medium depends on a number of factors such as absorption, scattering, diffraction effects and beam spreading. Their influence with relation to frequency selection for inspection becomes very important. The points to be considered while selecting a suitable frequency for testing are:

2.8.4 Grain Size and Flaw Size

Higher frequencies suffer higher attenuation of ultrasonic energy in the material. It is necessary to note the small reflector to be detected and the structure of the material while selecting the frequency. Coarse or large grain material can cause scatter and loss of reflected energy, particularly when the grain size and the wavelength are comparable. If the frequency is lowered to a point where the wavelength is considerably greater than the grain size, scattering losses are reduced but the sensitivity is also lowered.

2.9 Types of Transducer

Ultrasonic transducers are manufactured for a variety of applications and can be custom fabricated when necessary. Careful attention must be paid to selecting the proper transducer for the application. A previous section on Acoustic Wavelength and Defect Detection gave a brief overview of factors that affect defect detectability. It is important to choose transducers that have the desired frequency, bandwidth, and focusing to optimize inspection capability. Most often the transducer is chosen either to enhance the sensitivity or resolution of the system. Figure 2.18 shows the different types transducer available in market.



Figure 2.18: Types of Transducer

Transducers are classified into groups according to the application.

2.9.1 Contact Transducers

Contact transducers are used for direct contact inspections, and are generally hand manipulated. They have elements protected in a rugged casing to withstand sliding contact with a variety of materials. These transducers have an ergonomic design so that they are easy to grip and move along a surface. They often have replaceable wear plates to lengthen their useful life. Coupling materials of water, grease, oils, or

commercial materials are used to remove the air gap between the transducer and the component being inspected. The Figure 2.19 shows the Contact transducer.



Figure 2.19: Contact transducers

2.9.1.1 Different types of Contact Transducers

Contact transducers are available in a variety of configurations to improve their usefulness for a variety of applications. The flat contact transducer shown above is used in normal beam inspections of relatively flat surfaces, and where near surface resolution is not critical. If the surface is curved, a shoe that matches the curvature of the part may need to be added to the face of the transducer. If near surface resolution is important or if an angle beam inspection is needed, one of the special contact transducers described below might be used.

Dual element transducers contain two independently operated elements in a single housing as shown in the Figure 2.20. One of the elements transmits and the other receives the ultrasonic signal. Active elements can be chosen for their sending and receiving capabilities to provide a transducer with a cleaner signal, and transducers for special applications, such as the inspection of coarse grained material. Dual element transducers are especially well suited for making measurements in applications where reflectors are very near the transducer since this design eliminates the ring down effect that single-element transducers experience (when single-element transducers are operating in pulse echo mode, the element cannot start receiving reflected signals until the element has stopped ringing from its transmit function). Dual element transducers are very useful when making thickness measurements of thin materials and when inspecting for near surface defects. The two elements are angled towards each other to create a crossed-beam sound path in the test material

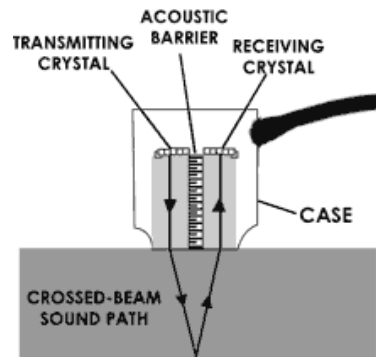


Figure 2.20: Dual element transducers

Delay line transducers provide versatility with a variety of replaceable options as shown in the Figure 2.21. Removable delay line, surface conforming membrane, and protective wear cap options can make a single transducer effective for a wide range of applications. As the name implies, the primary function of a delay line transducer is to introduce a time delay between the generation of the sound wave and the arrival of any reflected waves. This allows the transducer to complete its "sending" function before it starts its "listening" function so that near surface resolution is improved. They are designed for use in applications such as high precision thickness gauging of thin materials and delamination checks in composite materials. They are also useful in high-temperature measurement applications since the delay line provides some insulation to the piezoelectric element from the heat.

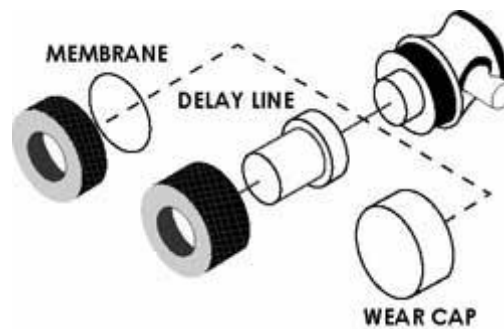


Figure 2.21: Delay line transducers

Angle beam transducers and wedges are typically used to introduce a refracted shear wave into the test material. Transducers can be purchased in a variety of fixed angles or in adjustable versions where the user determines the angles of incidence and refraction as shown in the Figure 2.22. In the fixed angle versions, the angle of refraction that is marked on the transducer is only accurate for a particular material,

which is usually steel. The angled sound path allows the sound beam to be reflected from the back-wall to improve detectability of flaws in and around welded areas. They are also used to generate surface waves for use in detecting defects on the surface of a component.

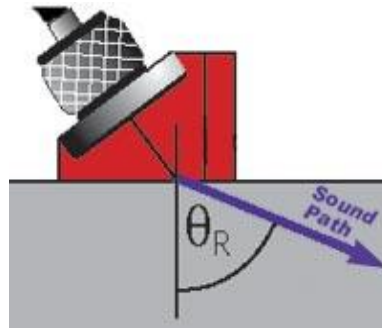


Figure 2.22: Angle beam transducers

Normal incidence shear wave transducers are unique because they allow the introduction of shear waves directly into a test piece without the use of an angle beam wedge. Careful design has enabled manufacturing of transducers with minimal longitudinal wave contamination. The ratio of the longitudinal to shear wave components is generally below -30dB.

Paint brush transducers are used to scan wide areas. These long and narrow transducers are made up of an array of small crystals that are carefully matched to minimize variations in performance and maintain uniform sensitivity over the entire area of the transducer. Paint brush transducers make it possible to scan a larger area more rapidly for discontinuities. Smaller and more sensitive transducers are often then required to further define the details of a discontinuity.

2.9.2 Immersion Transducers

Immersion transducers do not contact the component. These transducers are designed to operate in a liquid environment and all connections are watertight. Immersion transducers usually have an impedance matching layer that helps to get more sound energy into the water and, in turn, into the component being inspected. Immersion transducers can be purchased with a planer cylindrically focused or spherically focused lens as shown in the Figure 2.23. A focused transducer can improve the sensitivity and axial resolution by concentrating the sound energy to a smaller area.

Immersion transducers are typically used inside a water tank or as part of a squirter or bubbler system in scanning applications.

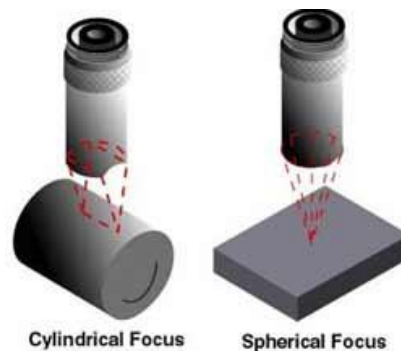


Figure 2.23: Immersion transducers

2.9.3 Low Frequency Transducer

The conventional flaw detectors using frequencies 1 MHz and above cannot be used for the inspection of materials with heterogeneous and coarse grain structure, due to high attenuation and scattering effects at these frequencies. Low frequencies (20 to 50 kHz) are generally used for materials like concrete, timber, rock, refractories etc.

Out of various transducers discussed, contact Transducers are widely used in the area where there is direct contact between the transducer and testing work piece and these transducers are used to test plates in air.

Immersion Transducers are used for testing the specimen which is immersed in fluids where there must be tight sealing for the transducer to work in fluids. These transducers are placed at an angle to the plate to excite the mode to find the defect in the plates.

The prominent works carried out by various researchers in the area of damage detection in plates are discussed below.

Lamb (1904) made the first investigation of pulse propagation in a semi-infinite solid.

Timoshenko (1921) developed a theory for beams that accounted for shearing deformation.

Mindlin (1955) presented an approximate theory for waves in a plate that provided a general basis for development of higher-order plate and rod theories.

Boller C (1975) went through the study of Structural health management of ageing aircraft and other infrastructure.

Doyle and Scala (1978) studied both bulk and surface wave ultrasonic methods for the measurement of the depth of surface-breaking cracks. They presented techniques for measuring crack depth by studying the scattered pulse amplitude, by using time-of-flight methods, or by carrying out ultrasonic spectroscopic analysis.

Abrahams et al. (1992) have examined the scattering of Rayleigh waves by an inclined two dimensional plane surface breaking crack in an isotropic elastic half-plane.

Rose et al. (1997) studied the potential use of guided waves for defect characterization is studied. The influence of defect shape and size on transmitted and reflected fields is considered. Using the hybrid boundary element technique, the reflection and transmission coefficients for selected guided wave modes are numerically calculated and compared to experimental data.

Lowe et al. (1998) presented the technique of wave propagation and their sensitivity to defects through pipes using pulse echo. Issues of importance were the selection of the optimum guided wave modes and the establishment of relationships between the defect size and the strength of wave reflection.

Gilchrist (1999) showed how horizontal symmetric crack-like defects can be detected rapidly in thin isotropic plates by using longitudinal ultrasonic waves.

Deng et al. (1999) studied the structural health monitoring using active sensors and wavelet transforms. In these methods, wave propagation signals were collected using arrays of piezoelectric transducers placed on or embedded in a structure. The collected signals were analyzed using appropriate wavelet transforms. The final interpretation of the sensor signals was based on signal patterns uncovered by the wavelet transforms in correlation with elastic wave propagation theory.

Giurgiutiu et al. (2001) explored the capability of embedded piezoelectric wafer active sensors (PWAS) to excite and detect tuned Lamb waves for structural health monitoring.

Paul Fromme et al (2001) studied the scattering of the first antisymmetric Lamb wave mode A₀ at obstacles in plate-like structures is studied in this dissertation. The propagation in an isotropic, homogeneous plate, the scattering at a circular hole, and the scattering at a hole with a defect are investigated experimentally and theoretically. Guided flexural waves have the advantage of propagating over large distances in plates, thus allowing the fast and efficient detection of defects in large structures

Pavlovik et al (2001) investigated the propagation of waves through an elastic solid and found that two types of waves, longitudinal and transverse, could exist. Poisson also solved the problem of the radial vibrations of a sphere

Joseph L. Rose et al (2003) did experimentation on Surface breaking half elliptical shaped defects of three opening lengths and through-wall depths of 10–90% on a 10 mm thick steel plates were considered. The reflection and transmission coefficients of both Lamb and shear horizontal (SH) waves over a frequency range 0.05–2 MHz were studied.

Bhalla et al. (2005) investigated Wave propagation approach for NDE using surface bonded piezoceramics.

K. Edalati, et al (2005) studied Two ultrasonic lamb wave techniques, pulse-echo (a₁ mode emitter) and emission (s₁ mode emitter), were used for interpretation of notch defects with depths of 10%, 30% and 60% of plate thickness. Thickness of plate was

2 mm and the nominal center frequency of transducers was 2 MHz. It was observed that these techniques are sensitive to evaluate defects, especially in short probe to defect distances. Also, it was found that amplitude analysis can give some qualitative information about defects depth by using Distance-Amplitude-Correction curves, but it was not sometime repeatable.

Mukherjee et al. (2005) did the characterization of discretely graded materials using acoustic wave propagation. C. the Guided waves can be used efficiently, and both for measuring the length of a rod embedded in concrete and for estimating the amount of delamination between a steel rock bolt and concrete.

Fromme et al. (2006) explained Guided ultrasonic waves can propagate over large distances in thin structures like the hull plates of a ship and allow for efficient nondestructive testing of such structures with limited access. The sensitivity of guided ultrasonic wave inspection and monitoring for damage detection close to structural features, e.g., stiffeners, in plate like structures, has been investigated in a two dimensional Finite Element Model (FEM). The combined interaction of the guided ultrasonic waves with defects and structural features in large structures has been modeled numerically to predict and improve the sensitivity and reliability of damage detection.

Li Yibo et al. (2006) did experimental work on energy attenuation of ultrasonic guided waves going through girth welds.

Mukherjee et al. (2006, b) studied the use of acoustic wave propagation for the characterization of discretely graded materials. In this research work, a simple one dimensional model was proposed to study the stress waves in discretely graded media. The model used spectral approach to determine the stresses due to the incident and reflected waves in FGMs.

Aggelis and Shiotani (2007) studied repair evaluation of concrete cracks using surface and through-transmission wave measurements. Rayleigh waves demonstrate the filling condition of the material into the shallow layer near the surface while tomography using longitudinal waves through the thickness yields information about the area inside the structure. Wave propagation dispersion features are exploited by

the proposed tomography at different frequencies, demonstrating that higher frequencies lead to more accurate characterization.

Vermani et al. (2008) worked on damage detection in reinforcing Steel Bar using Ultrasonic Wave Propagation.

CHAPTER 4

DAMAGE DETECTION IN PLATES

Damage detection has been an important area of concern in the design, operation, maintenance and repair of many military and civil naval structures and equipment involving plate structures. Current work proposes to use ultrasonics to monitor damages in the plates utilizing Lamb Waves which subsequently would be made incident on the submerged damaged specimens at varying critical angles. The reflected /scattered signals would be received at particular angles. The variations in the signals received should lead one to identify, locate and evaluate damage and determine the residual life of the subject plate specimens.

4.1 Selection of Lamb Wave Modes

The key problem associated with the quantitative measurement of the characteristics of propagating Lamb modes is that more than one mode can exist at any given frequency. Excitation with transducers of finite dimensions inevitably means that all the modes possible at any particular frequency of excitation are produced so it is not possible to separate the modes simply by transforming from the time domain to the frequency domain. Also, since the excitation will not be single frequency, dispersion will also be present leading to complicated time domain signal. Therefore, the time history of the response of the plate is usually multi-mode and dispersive. In such cases the shape of the lamp wave packet is strongly dependent on propagation distance.

When the wave hits the interface different modes are generated with different velocities and energy. Each mode can be separately excited in the plate using Snell's law. Since velocity of each mode for each frequency will be different, by using Snell's law required mode can be excited in the plate. Disperse curves are used to find the velocity of any particular mode by using software DISPERSE.

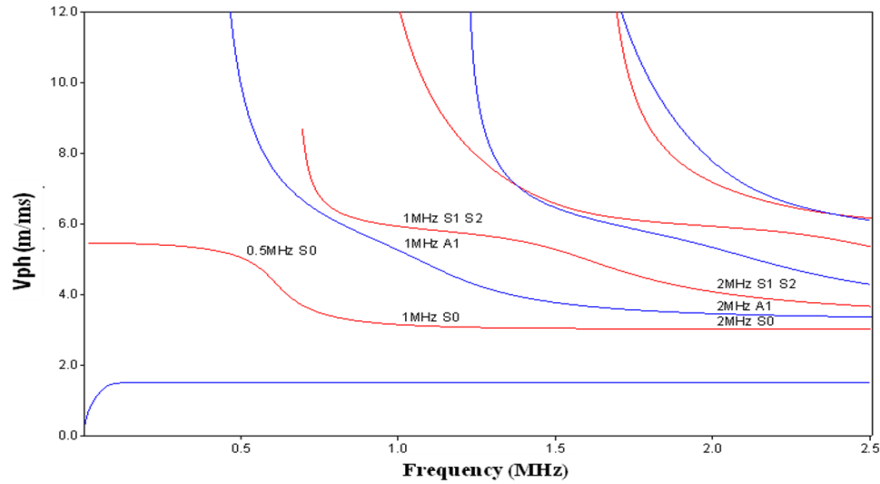


Figure 4.1: Disperse Curves of 4mm Plate surrounded with water

Interface geometry is modeled in DISPERSSE and different lamb wave modes are generated in the plate for different frequencies. Regenerating a particular mode, say S_1 mode ,knowing the Velocity of ultrasonic wave in water is 1.5km/s and the velocity of S_1 mode of frequency is 5.268km/s is found using DISPERSSE,

$$\text{Angle of incident} = \sin^{-1}\left(\frac{1.5}{5.268}\right) = 16.5^\circ . (S_1 \text{ modes}).$$

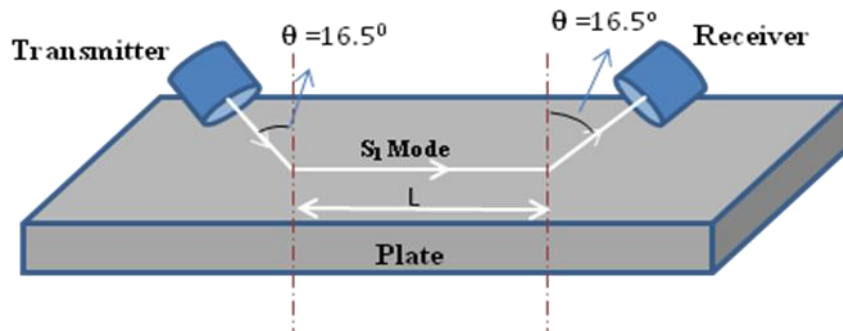


Figure 4.2: Transducers arranged at an angle to the Plate

4.2 Experimental Study

Testing using ultrasonics is done on the plates of thickness 12mm where the transducer is kept contact with the plate. This testing is known as testing of plates in air. Many problems are faced during testing of plates in direct contact with object specimen. To solve this problem the testing is carried out in water. This is known as testing in water.

4.2.1 Testing of Plates in Air

4.2.1.1 Parametric Study

Testing of Plates in Air is done on steel plates of thickness 12mm. The defect is simulated on the plates for testing. Defect of type notch of varying depth is made in the plate at $L/2$, $2L/3$ and $L/3$ distance as shown in the Figure 4.3. Here, the Transducers are arranged parallel to plate length as shown in Figure 4.4.

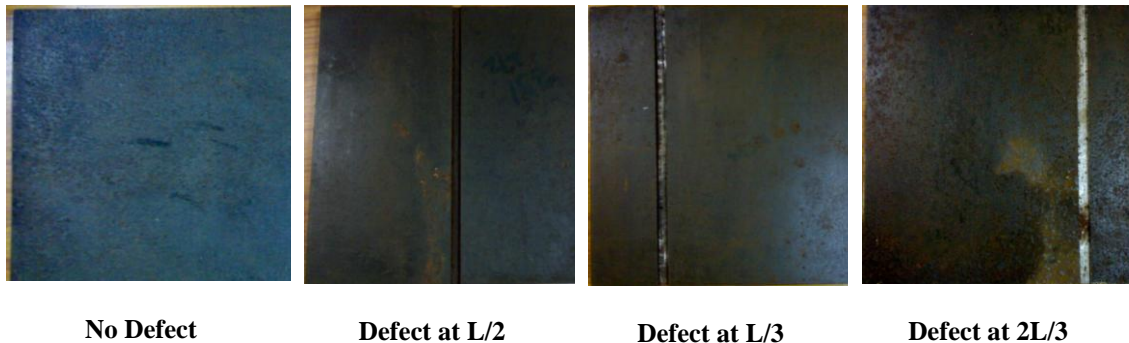


Figure 4.3: Plates with Notch Defects at different locations (200mm x 200mm x 12mm)

4.2.1.2 Experimental Setup

The experimental setup consists of pulser/receiver which generates the pulse for every 5 ns. This is sent to the transducer which transfers the pulse to ultrasonic wave. Transmitter transducer is kept in contact with the plate using the couplant and the other end the receiver transducer is arranged in the same way. This transducer is connected back to the pulser/receiver, sends the signals to the digitizer card which is connected to computer hardware.

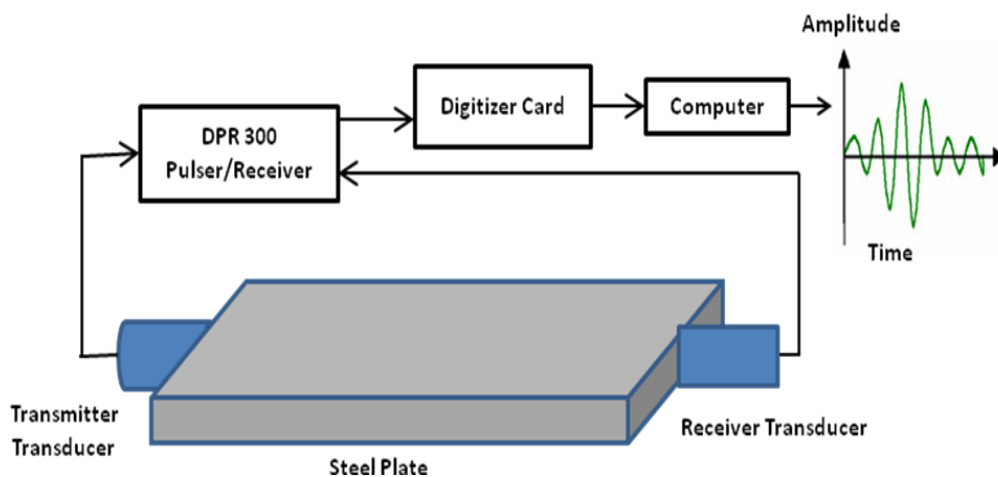


Figure 4.4: Experimental Setup for Testing in Air

a) Transducer

A contact transducer is a single element longitudinal wave transducer intended for use in direct contact with a test piece. It can be used in straight beam flaw detection and thickness gauging, detection and sizing of delamination, material characterization and sound velocity measurements, inspection of plates, billets, bars, forgings castings, extrusions, and a wide variety of other metallic and non-metallic components. ACCUSCAN "S" series have longer wave form duration and a relatively narrow frequency bandwidth.

b) Agilent Function 6000 Series Oscilloscope

A 100 MHz, 2-channel + 16 Logic Channels MSO with maximum sampling rate of 2 GSa/s was used. The analog input impedance of the 100 MHz oscilloscopes is fixed at 1 M Ω .

c) JSR Ultrasonics DPR 300 Pulsar/ Receiver System

DPR300 pulser produces a high voltage electrical excitation pulse and applies this pulse to the instrument's T/R connector. An ultrasonic transducer connected to the T/R connector via a length of 50 Ω coaxial cable is then employed to convert the electrical energy of the excitation pulse into an ultrasonic pulse that is propagated into a test material or medium.

With the DPR300 configured for pulse-echo mode operation, acoustic echoes reflected from interfaces or defects within the test material are converted by the transducer into electrical signals that are presented to the T/R connector of the DPR300. The low-noise DPR300 receiver amplifies these electrical signals, and the signals then pass through adjustable high pass and low pass filters. The DPR300 receiver gain is adjustable between -13 dB and 66 dB, and there are six high pass and six low pass filter settings for band-limiting the receiver frequency response. The amplified and filtered signals are available on the instrument's Receiver Output connector.

The DPR300 may also be used in transmission mode operation wherein a separate receiving transducer is used to detect acoustic pulses that have propagated through a test material or medium.

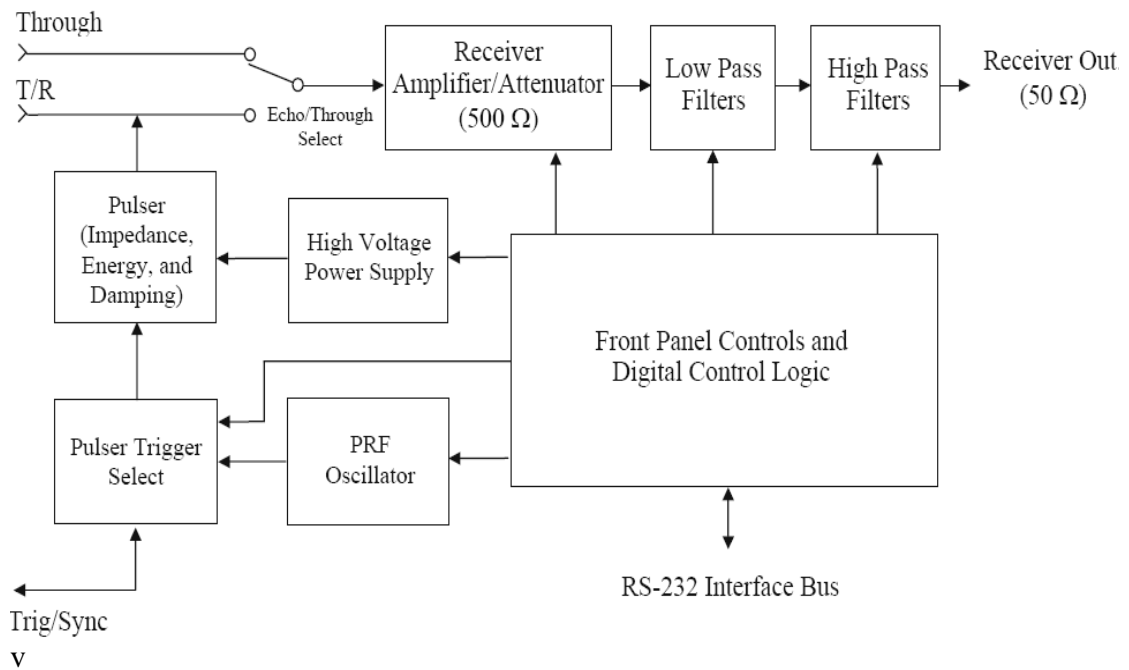


Figure 4.5: Layout of JSR Pulse Generator

PRF Oscillator & Pulser Trigger control: The internal PRF oscillator generates repetitive trigger pulses for the pulser subsystem under the control of the PRF control. Pulser Trigger control selects between the internal PRF oscillator and an external source applied to the Trig/Sync connector as trigger sources for the DPR 300 Pulser.

Pulser (Impedance/Energy/Damping): The pulser generates an excitation pulse upon receiving a trigger event from a selected source. There are four energy and two impedance values, and the single Energy and impedance control adjusts the pulse energy and the pulser impedance.

Receiver amplifier: It controls the amplification or attenuation of signals processed by the DPR300 receiver. The receiver gain can be varied from -13dB to 66 dB.

Low Pass and High Pass filters: Low filters are available for reducing the bandwidth of the DPR300 receiver. High Pass filters are available for eliminating undesirable low frequency energy from the DPR300 receiver signal. High pass filtering can be used as a means of providing faster receiver recovery from strong signals such as the excitation pulse or strong interface echoes.

Table 4.1: Configuration of JSR Pulse Generator

Pulser	
Pulse Type	Negative Spike Pulse
High Voltage Supply	100V to 475V
Initial Transition (Fall Time)	<5 ns (10-90%) typical for 475V pulsers
Pulse Amplitude	-475V peak. Amplitude depends on Energy, Impedance, Damping control settings, and pulser type
Pulse Energy	1.55 μ Joules minimum, 304 μ joules maximum for 475V pulsers. Dependent upon energy and voltage setting
Pulse Duration	Typically 10-70 ns FWHM for 50 load. Function of the Energy, Impedance, and Damping controls
Damping	16 Damping values: 331, 198, 142, 110, 92, 77, 67, 59, 52, 47, 43, 39, 37, 34, 32, and 30 Ω .
Mode	Pulse-echo or through transmission
Through Mode Isolation	Typically 80 dB at 10 MHz
Pulser Repetition rate	Internal: 100 Hz -5 kHz for 475V pulsers. External: 0 -5 kHz for 475V pulsers.
Sync Output	Maximum +5 V, $t_r < 30$ ns, $t_w = 50$ ns. min. TTL and CMOS compatible. Minimum value of load impedance is 50
Pulser Trigger Source	Selectable by computer between internal oscillator and external source
External Trigger Input	3 -5 V positive going pulse. Triggering will occur synchronously with leading edge of trigger signal. TTL and CMOS compatible
Receiver	
Gain	-13 to 66 dB in 1 dB steps controlled by the host computer
Phase	0o (noninverting)
Input Impedance	500(through transmission)

Bandwidth	.001-35 MHz (-3 dB) or .001-50 MHz
High Pass Filter	DC,1, 2.5, 5, 7.5 and 12.5 MHz
Low Pass Filter	3,7.5,10,15,22.5 (35 MHz BW) or 5,10,15,22.5,35 (50 MHz BW)
Receiver Noise	Typically 49 μ V pk-pk input referred(measured at 60dB,35 MHzbandwidth)
Output Impedance	50
Output Voltage	\pm 0.5 V into 50

Dual-Channel High-Resolution Waveform Digitizer

Model DC438 Dual-channel, 12-bit, 100 MHz, 200 MS/s, 4 M point acquisition memory card was used to capture the waveform. Waveforms are transferred directly into the digitizer large acquisition memories so that complex signals can be stored over very long time periods. Large memories are essential for maintaining fast sampling rates and therefore timing resolution.

Table 4.2: Configuration of Digitizer Card

Model DC438	
Bandwidth (-3 dB)	DC to 100 MHz
Full Scale Range (FSR)	250 mV, 500 mV, 1 V, 2 V, 5 V and 10 V
Impedance	50 Ω \pm 1% @ DC
Connector	BNC, gold-plated
Channels	Two
Coupling	DC
Maximum Input Voltage	\pm 10 V DC (2 W) or 10 V RMS at 50
Bandwidth Limit Filter	35 MHz 2-pole Bessel filter (DC438)
Minimum Amplitude	1 V pk-pk
Impedance	50 Ω

4.2.1.3 Experimental Details

To simulate damage area reduction was done at three different locations along the length of the plate. The magnitude of the defect was also varied at a particular location. Pulse echo and through transmission method were used for characterizing

the damage. To find the location of crack, Pulse Echo method was used and to find the extent of damage Through Transmission was used. The depth of the crack is the measurement of the transit time of the wave diffracted by the tip of the crack. Longitudinal wave was generated by placing the transducers normal to the cross section of the plate as shown in Figure 4.4. The nature of these waves is dispersive meaning that their propagation shall lead to generation of multiple modes at a given frequency. In through transmission method, two probes were used one as an actuator for sending the waves at one end and another as a receiver for receiving the waves at the other end of the plate.

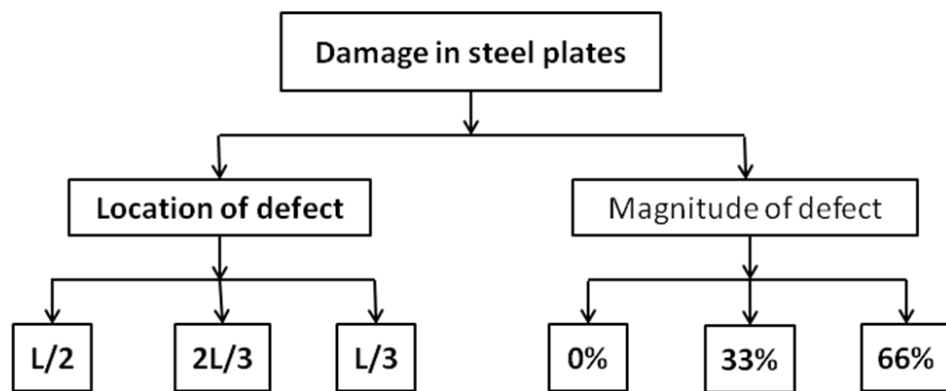


Figure 4.6: Methodology of damage detection in plates

4.2.1.4 Pulse Echo Testing

In nondestructive testing of metals, the ultrasonic pulse-echo (PE) technique has proven to be a reliable method for locating cracks and other internal defects. An electro-mechanical transducer is used to generate a short pulse of ultrasonic stress waves that propagates into the object being inspected. Reflection of the stress pulse occurs at boundaries separating materials with different densities and elastic properties. The reflected pulse travels back to the transducer that also acts as a receiver. The received signal is displayed on an oscilloscope, and the round trip travel time of the pulse is measured electronically. By knowing the speed of the stress wave, the distance to the reflecting interface can be determined.

➤ Location of damage

Location of damage was changed from L/2 location to L/3 and 2L/3 locations along the length of the plates. The Signals received from all the specimens (two samples each for % area reduction) was analyzed and compared with the healthy specimen. It was found that time of flight of peak from the crack changes with change in damage location.



Figure 4.7: Pulse Echo of Plates Testing in Air

The velocity of longitudinal wave in steel plates of young's modulus of elasticity as 200 GPa and density as 7800 Kg/m³ is calculated using the formula.

$$V_{theo} = \sqrt{\frac{E}{\rho}}$$

Therefore,

$$V_{theo} = 5063 \text{ m/s}$$

The velocity of the wave in plates is known and distance traveled by the wave is known. Then the time of flight is calculated as

$$D = \frac{VT_{theo}}{2}$$

$$T_{theo} = \frac{2D}{V_{theo}}$$

The time of flight of wave in healthy specimen of 9 inches length is 9.86E-5 sec and as per the graphs it is 9.89E-5 sec. Similarly the time of flight of wave from the crack at L/2 length is 4.082E-6 sec theoretically and we can see from the graph that it comes out to be 4.13E-4 sec. Similar results were found when specimens were tested for crack at 2L/3 length.

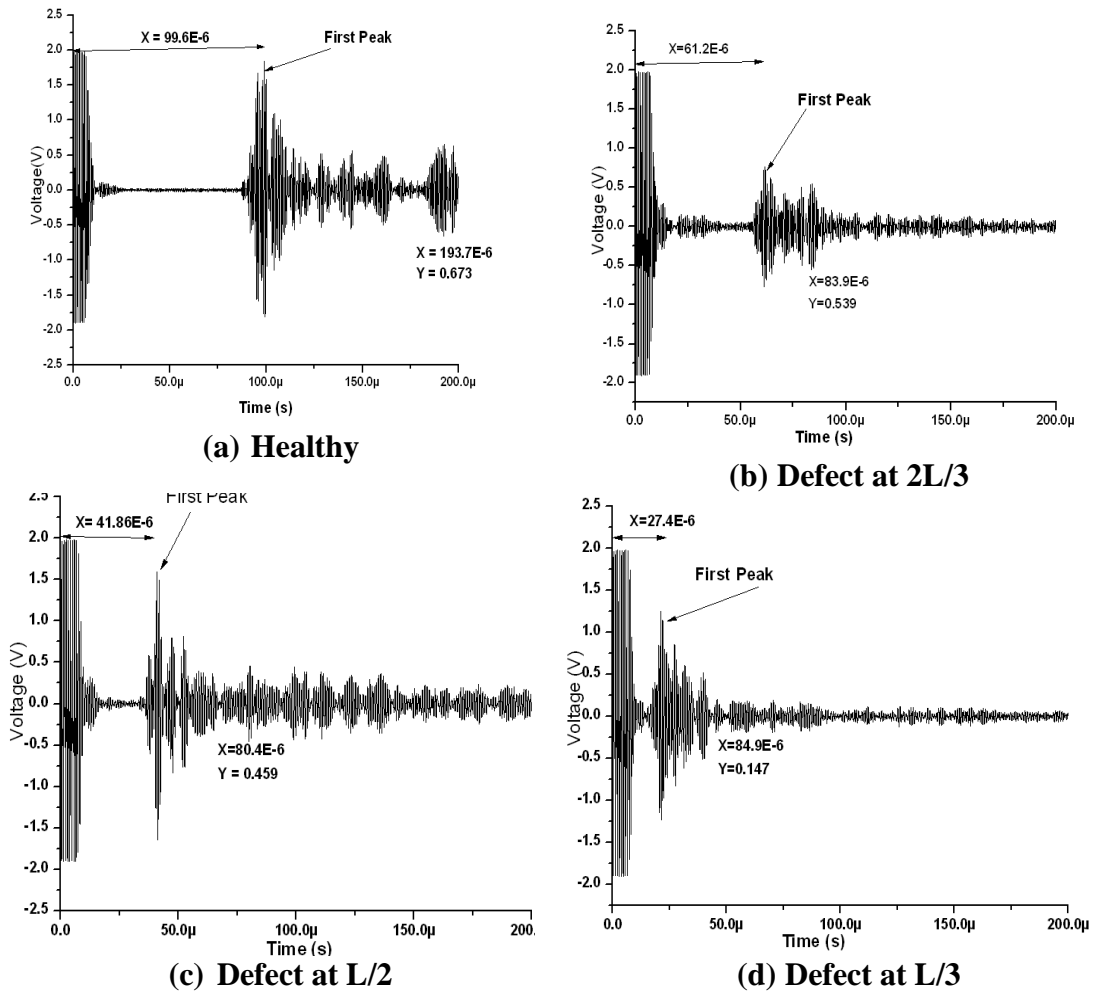


Figure 4.8: Signatures of Pulse Transmission of Defects

Table 4.3: Pulse Echo of steel plate with change in Defect Location

% Defect	Healthy	2L/3	L/2	L/3
Time of Flight (t_{exp})	9.89E-5	61.2E-6	4.082E-5	27.4E-6
Time of Flight (t_{theo})	9.86E-5	61.3E-6	4.13E-5	30.2E-6

From the Table 4.3, it is clear that as the defect location on the plate moves away from the transducer from L/3 \rightarrow L/2 \rightarrow 2L/3 \rightarrow healthy, the time of flight for the first peak in pulse echo will increase since the distance travelled increases, velocity of wave in the plate being the same.

4.2.1.5 Through Transmission

In Through transmission method, first and second peak was reported in healthy as well as cracked specimen. In healthy specimen the first peak is that obtained at the other end as shown in Figure 4.9. In cracked specimen the first peak was that obtained

at the other end just like in healthy specimen and second peak is received after reflecting from the crack as shown in Figure 4.10.

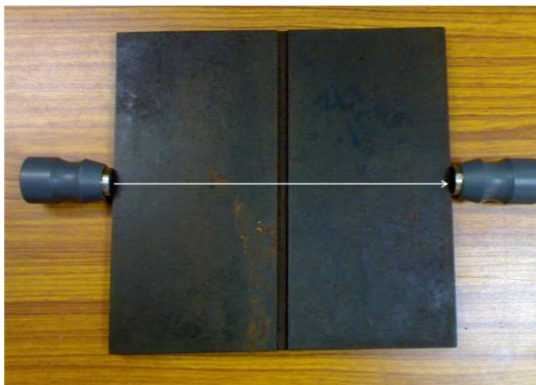


Figure 4.9: First Peak

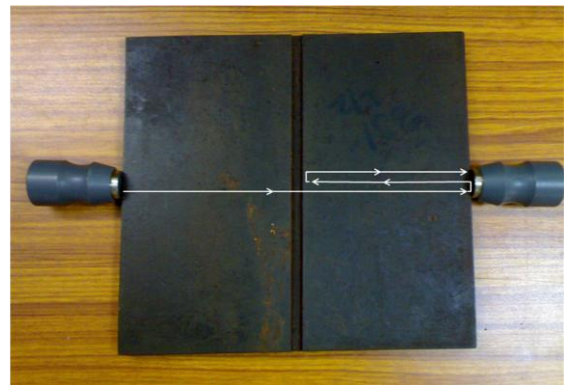
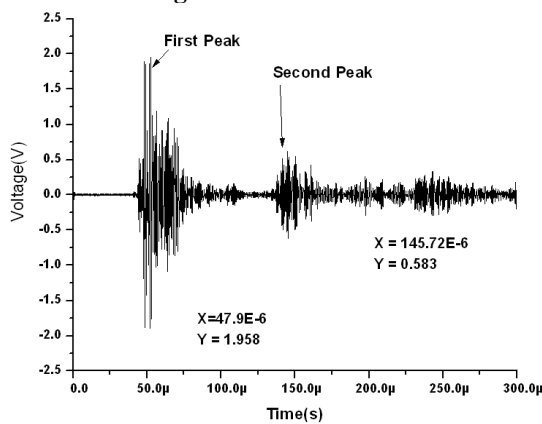
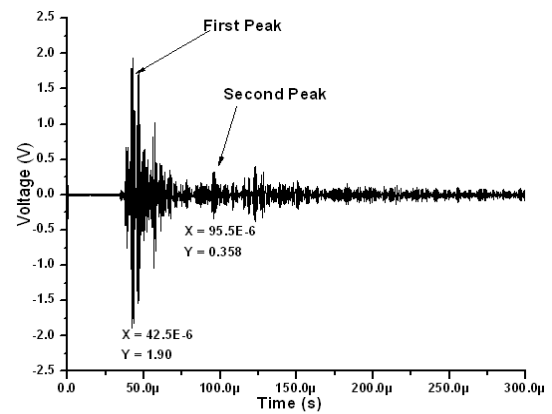


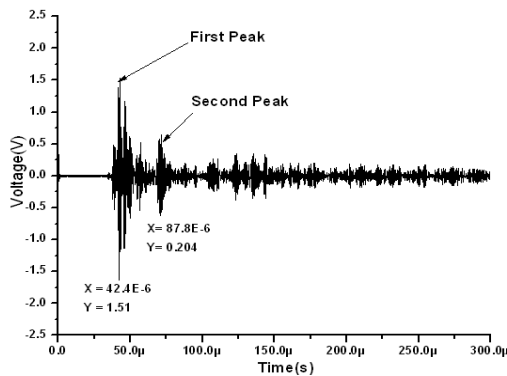
Figure 4.10: Second Peak



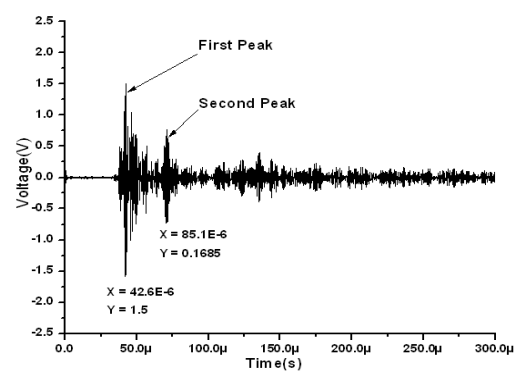
0% Defect



16.6% Defect



33.3% Defect



66.6% Defect

Figure 4.11: Signatures of Through Transmission of Defects

Table 4.4: pk –pk voltage amplitude for change in Defect Magnitude (L/2)

% Defect	0%	16.6%	33.3%	66.6%
pk –pk Voltage (V)	3.783	3.742	3.13	2.77

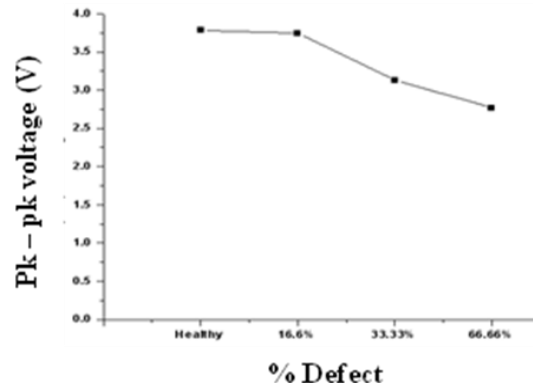


Figure 4.12: Through Transmission Trend

As the percentage of damage increases the voltage amplitude decreases. By knowing the relative drop in voltage amplitude with damage an idea about the severity of damage can be judged

So damage detection can be easily made by effective combination of pulse echo and through transmission technique.

In testing in air, the plates are tested by keeping the transducer head in contact to the plate along the thickness as shown in figure 4.9. Due to this, number of modes are generated in the plate because the wave propagates perpendicular to interface. So that the modes cannot be distinguished from each other. This problem was overcome by testing in water where a particular mode excited in the plate in arranging the plate at particular angle as discussed earlier. The transmitter transducer as well as receiver transducer are kept at same angle with the plate.

4.2.2 Testing of Plates in Water

The plate and the transducer are immersed in water where water becomes couplant for the transducer to send waves into the plate. In this the transducers are kept at an angle to the surface of the plate as shown in the Figure 4.13. For generating different mode, the incident angles are changed. The study is carried out on two different plates of thicknesses

- 1 4mm
- 2 6mm

The defects simulated on the plates are:

- 1 Notch of varying depth
- 2 Holes of varying depth

- 3 Punch of varying depth
- 4 Holes with varying diameter.

In this testing, a water tank of 42 x 28 x 24 cubic inches and a mechanism to move and rotate the transducer to required position is used for testing as shown in the Figure 4.13.

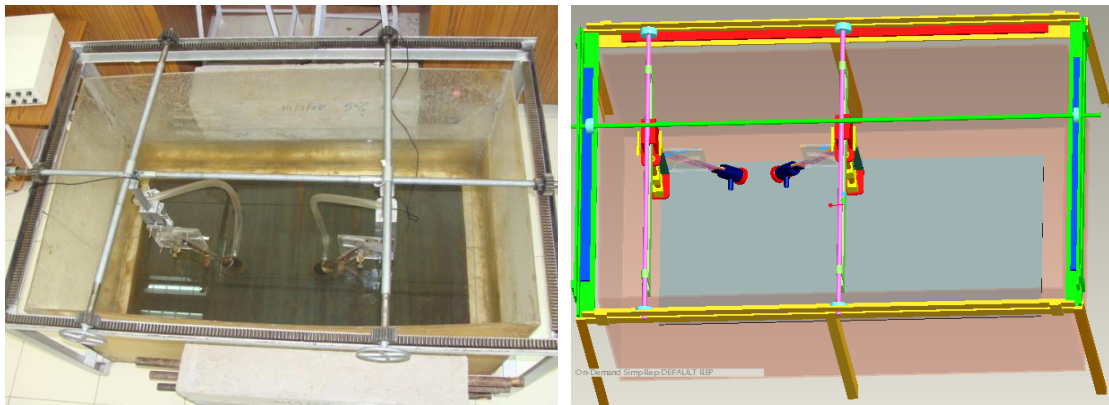


Figure 4.13: Four axis mechanism to scan Plates

4.2.2.1 Excitation frequency and setup

Transducers with center frequencies of 0.5MHz, 1 MHz and 2 MHz were used for the experiments. The transducers were driven by a Pulser/receiver system with maximum gain of 67 dB and maximum input voltage of 475V. An external PC and Digitizer card was used to capture the received signal and for further processing. A mechanism has been designed for testing of plates in submerged condition with water as fluid and as natural couplant, the details of the setup is shown in Figure 4.13.

This mechanism has four degree of freedom, three translations for positioning of transducer over plate and one rotation to arrange the transducer in a specific angle so as to get guided waves. The transducer was mounted in a holder and coupled using an industrial coupling gel. The excitation signal consisted of a negative spike pulse with pulse duration ranging from 10-70 ns. The results illustrate that different frequencies and modes have different dispersion characteristics with a trend toward higher frequencies having slower energy transport velocities.

4.2.2.2 Mode selection in 6mm plate for all frequency

Plate with both side water is modeled in disperse software as shown in Figure 4.14. The angle of incidence is calculated using the velocity of the mode which is to be excite is found using the using the figure 4.15.

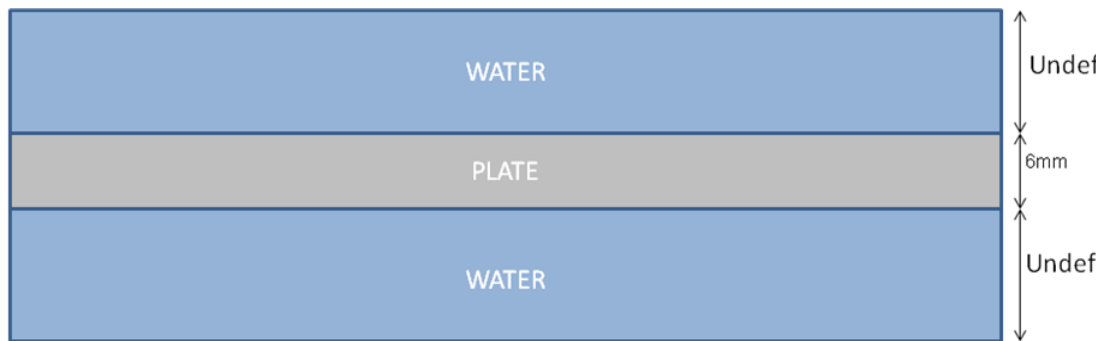


Figure 4.14: Modeling of 6mm Plate in Disperse

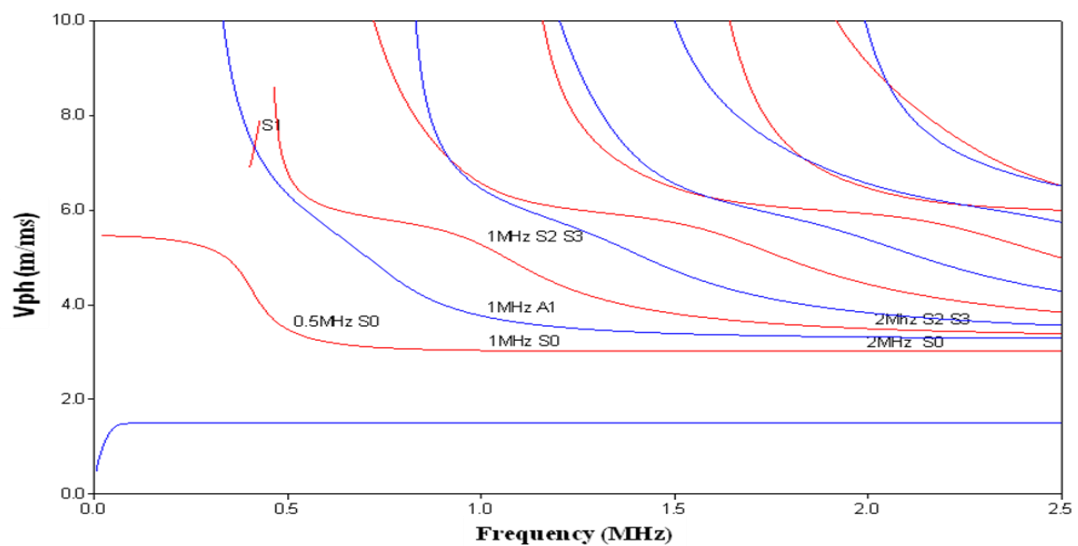


Figure 4.15: Selection of Disperse modes of 6mm Plate

In the Figure 4.15, red curves are symmetric modes and blue curves are anti-symmetric modes

Table 4.5: Angles to excite Modes in 6mm Plate

Excitation Frequency \ Excitation mode	0.5MHz	1MHz	2Mhz
S ₀	25.7°	30°	-
S ₁	-	-	-
S ₂	12.9°	16.5°	27.9°
S ₃	12.9°	16.5°	27.9°

4.2.2.3 Mode selection in 4mm plate for all frequency

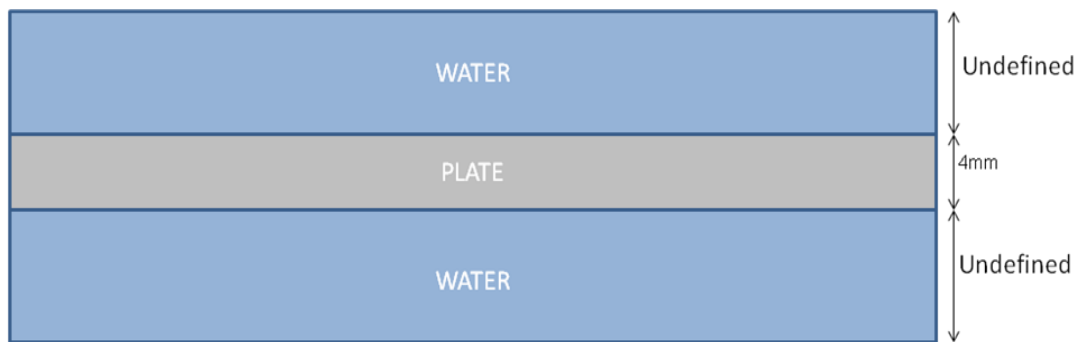


Figure 4.16: Modeling of 4mm Plate in Disperse

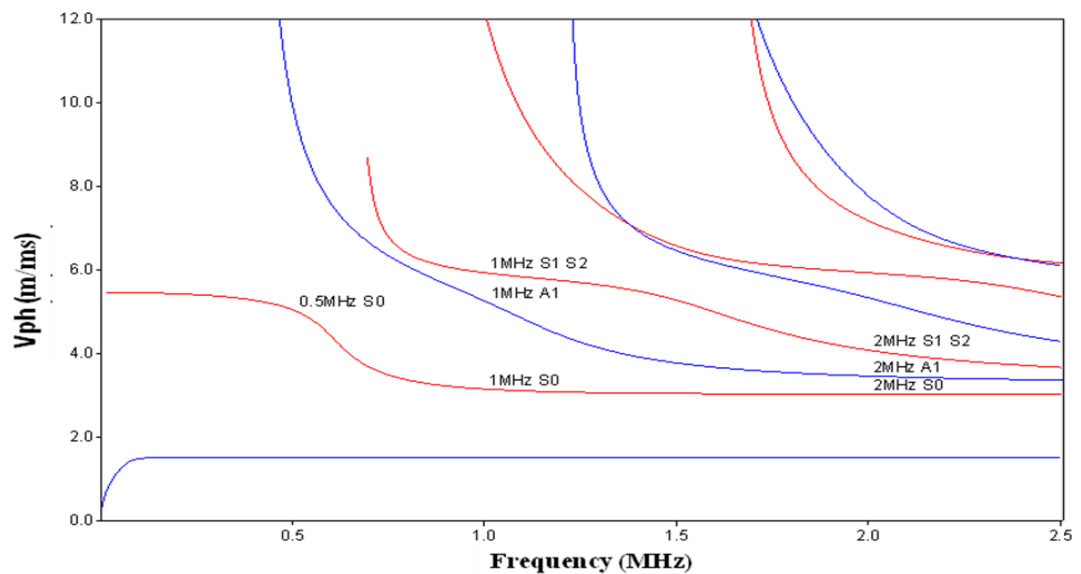


Figure 4.17: Selection of Disperse modes of 4mm Plate

Table 4.6: Angles to excite Modes in 4mm Plate

Excitation Frequency \ Excitation mode	0.5MHz	1MHz	2Mhz
S ₀	17.4°	28.5°	30°
S ₁	-	14.4°	21.6°
S ₂	-	14.4°	21.6°
S ₃	-	14.4°	21.6°

4.3 Scanning of Plates

Scanning of plates by arranging the transducer at an angle which is decided by examine the modes of each frequency. Then the plate to be tested is placed in tank and the area which has to be scanned is divided into grid point as shown in Figure

4.18. The total length and width of the plate is divided into small intervals. Each interval in x direction and in y direction may be equal or different depending on plate dimensions

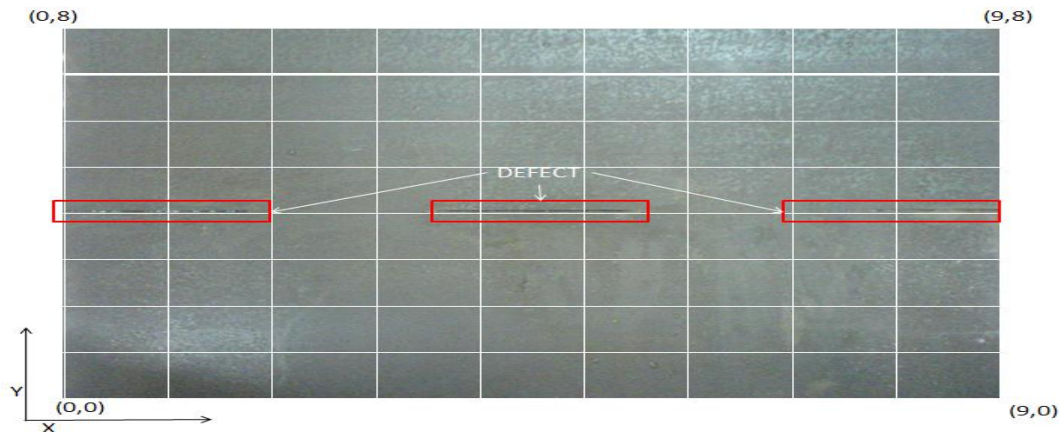


Figure 4.18: Plate with Grid Points for testing

Before beginning the scanning, the transmitter transducer is arranged at (0, 0) and receiver transducer is arranged at (0, 8) of the grid, then through transmission is taken at every grid point by moving in x-direction. If there is decrease in through transmission amplitude, then the setup is switched to Pulse echo and signal is send at that particular grid point with only transducer and is moved in y-direction until there is a change in pulse echo amplitude. All values of pulse transmission at all grid points are shown in 3D plot as shown in Figure 4.19.

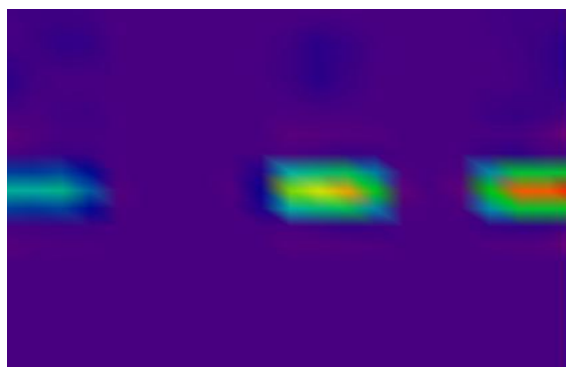


Figure 4.19: Example of Plate Scan

This chapter discusses about the experimental results of all the type of defect on each plate. Plates with seeded defects were first tested in air. Due to the problem of scattering and multiple modes generation, testing was then done in submerged state using water as a natural couplant. This chapter discusses experimental results for plates testing in water.

5.1 Testing for Notch Defect

4mm and 6mm plates were manufactured with seeded notch defects.

5.1.1 4mm Plate in water

Steel plate of thickness 4mm has a defect of type notch with varying depths. The notch depth is varied from 0.5mm, 1mm, 2mm to simulate 12.5%, 25% and 50% defect as shown in Figure 5.1. This is tested with 0.5MHz, 1MHz and 2MHz with different angles. Out of these angles, only suitable modes were taken for testing. Modes of each frequencies, only few were taken for testing because the rest of modes of different frequencies which gave very weak output signal were ignored and also have less energy to detect the defect on the plate.

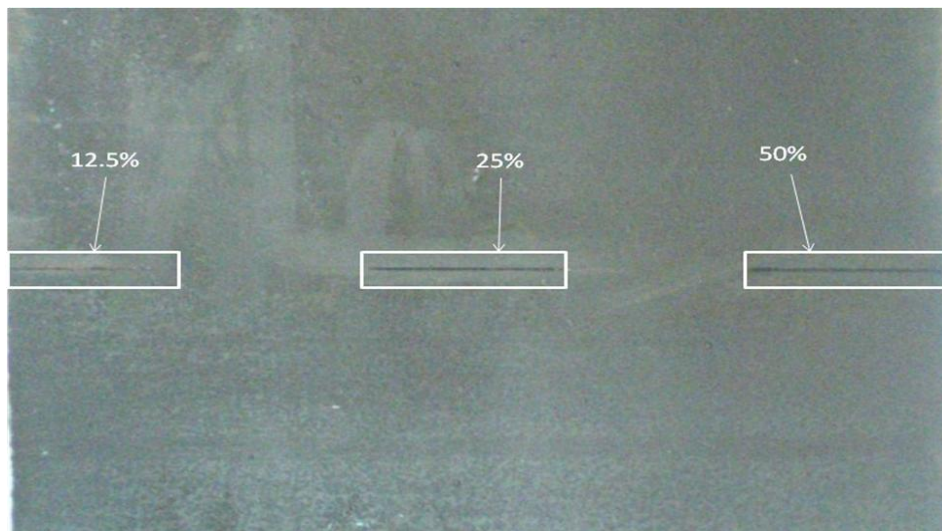


Figure 5.1: 4mm Plate with Notch Defect

Following modes and frequencies were used to excite different modes for 4mm plate with notch defects

- 1 0.5MHz with an angle of 17.4° degrees to excite S₀ mode.
- 2 1MHz with an angle of 14.2° to excite S₁, S₂ and S₃ modes and 16.6° to excite A₁ modes.
- 3 2MHz with an angle of 14.7° to excite S₄ mode, 21.6° to excite S₁, S₂ and S₃, 25.3° to excite A₁ mode and 30° to excite S₀ mode.

Table 5.1: pk –pk voltage of 4mm Plate with Notch Defect of all modes

	2MHz				1MHz		0.5MHz
MODE	S ₄	S ₁ S ₂ S ₃	A ₁	S ₀	S ₁ S ₂ S ₃	A ₁	S ₀
Angle	14.7°	21.6°	25.3°	30°	14.2°	16.6°	17.4°
% Damage	pk –pk voltage (V)						
0%	1.456	1.444	1.475	1.241	3.265	1.463	3.663
12.5%	0.795	1.441	1.445	0.941	2.716	1.154	3.081
25%	0.487	1.413	1.301	0.865	2.454	1.029	2.150
50%	0.366	1.332	1.271	0.789	2.142	0.967	1.423

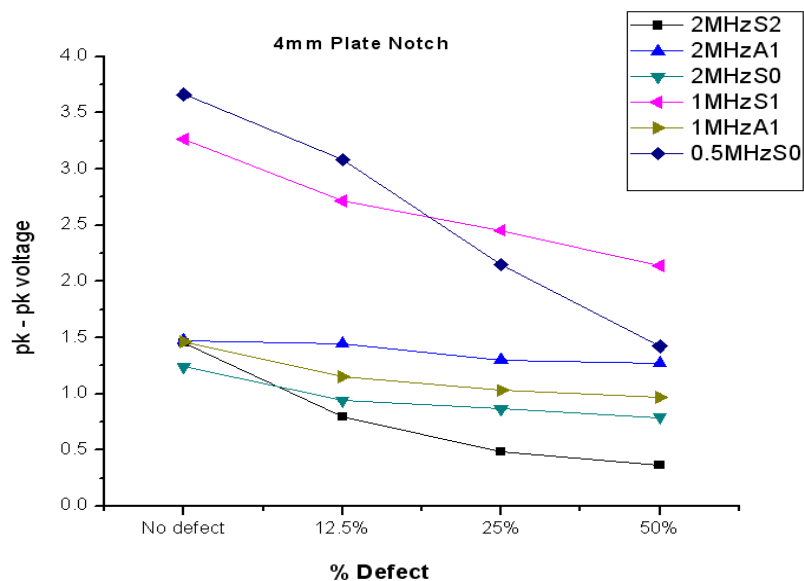


Figure 5.2: Trends of 4mm Plate of Notch Defect with Different Modes

It is very clear that 1MHz S₁, S₂ and S₃ modes are most sensitive to the notch defect. 1MHz S₁, S₂ and S₃ mode is highly energized mode and least attenuative mode, the peak to peak voltage amplitude with this mode is higher when compared with other modes. Disperse complemented by which shows that the modes suffers least attenuation in comparison to other modes in 4mm plate. From the DISPERSE, it is

clear that the mode S_1 is very less attenuate than other mode for 1MHz in 4mm plate as shown in figure 5.3.

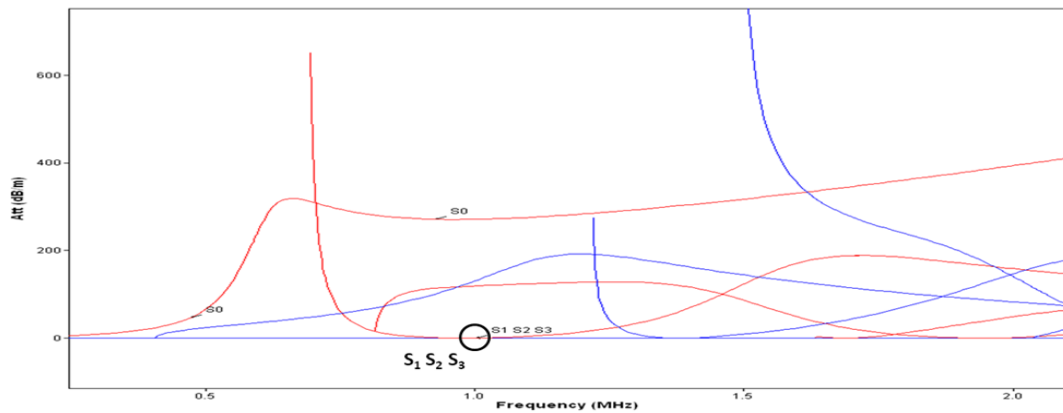


Figure 5.3: Attenuation Curves of 4mm Plate

So 1MHz S_1 , S_2 and S_3 modes were chosen for the testing of 4mm plate with notch type of defect. Magnitude of notch can be related to the fall in pk – pk voltage amplitude of the received signal (Figure 5.2). The total plate is scanned using 1MHz by arranging the transducer at an angle of 14.2 degrees to excite S_1 , S_2 and S_3 mode.

Scanning also gives an idea about the severity of damage. A plate was manufactured with 12.5%, 25% and 50% on the same plate and the transducers are moved. As the transducer nears the notch, the pk –pk voltage amplitude drastically falls as shown in boxes in Figure 5.4. Falls in amplitude with distance indicate the presence of notch. When there is fall in amplitude in through transmission, the plate is tested with pulse echo technique at every grid point by moving the transducer perpendicularly and the

pk –pk voltage amplitudes at every point are plotted as shown in Figure 5.5.

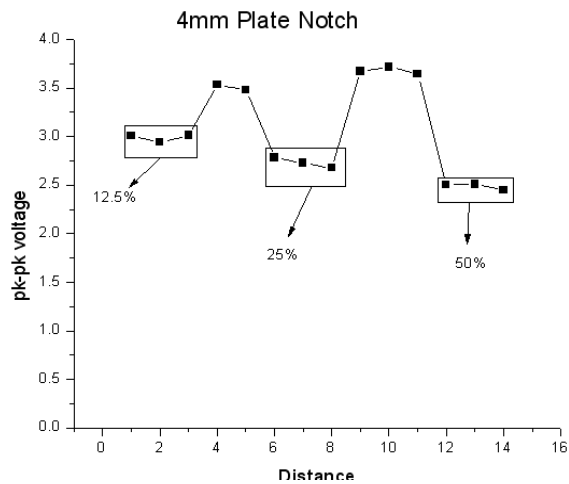


Figure 5.4: Through Transmission of 4mm Plate with Notch Defect at grid points

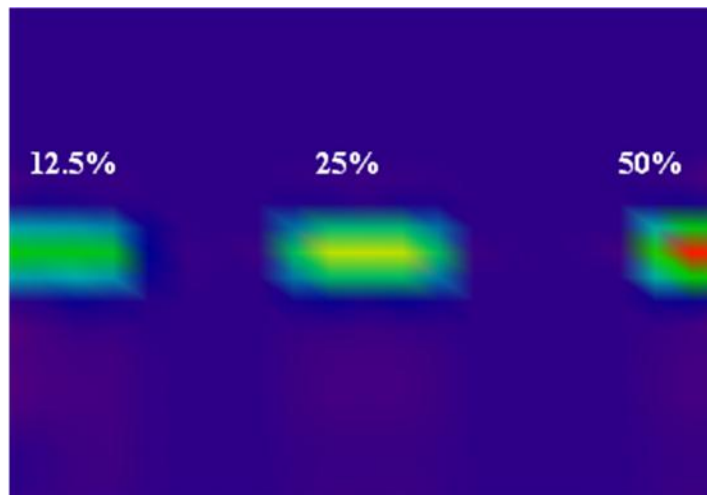


Figure 5.5: pk –pk voltage Pulse Echo Voltage amplitude (V) values at the Defects

Table 5.2: pk –pk voltage Pulse Echo Voltage amplitude (V) values at the Defects

	12.5%	25%	50%
pk –pk Voltage Amplitude(V)	2.62	3.131	3.783

5.1.2 6mm Plate in water

Steel plate of thickness 6mm has a defect of type notch with varying depths. The notch depth is varied from 1mm, 2mm, 4mm to simulate 16.6%, 33.3% and 66.6% defect as shown in Figure 5.6. This is tested with 0.5MHz, 1MHz and 2MHz with different angles. Out of these angles, only suitable modes were taken for testing. Modes of each frequencies, only few were taken for testing because the rest of modes

of different frequencies which gave very weak output signal were and also have less energy to detect the defect on the plate.

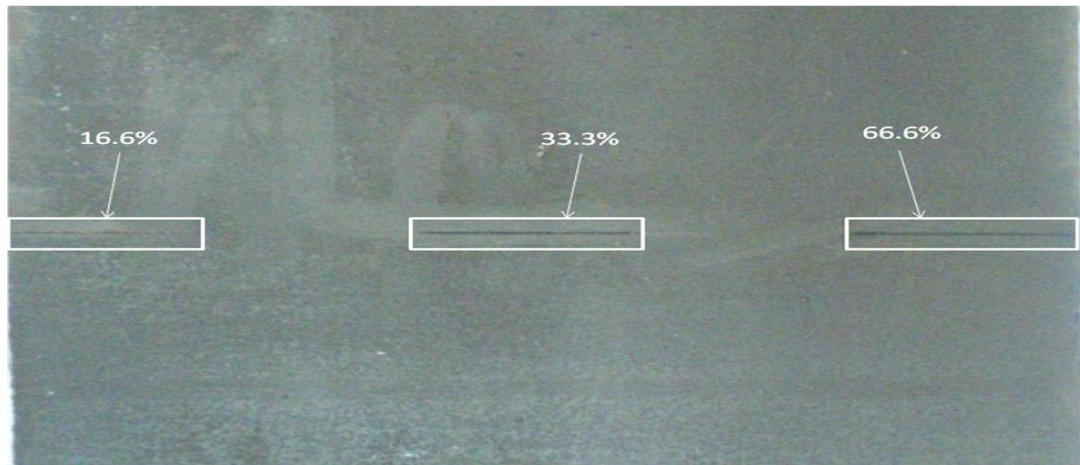


Figure 5.6: 6mm Plate with Notch Defect

Following modes and frequencies were used to excite different modes for 6mm plate with notch defects

- 1 0.5MHz with an angle of 25.7° degrees to excite S_0 mode.
- 2 1MHz with an angle of 16.5° to excite S_2, S_3 modes.
- 3 2MHz with an angle of 14.7° to excite S_5 mode and 27.9° to excite S_2 and S_3 modes.

Table 5.3: pk –pk voltage of 6mm Plate with Notch Defect of all modes

	0.5MHz	1MHz	2MHz	
Mode	S_0	$S_2 S_3$	S_5	$S_2 S_3$
Angle	25.7	16.5	14.7	27.9
% Damage	pk –pk voltage amplitude (V)			
0%	1.418457	3.23853	1.004639	1.016846
16.66%	0.638427	1.665967	0.587158	0.698242
33.33%	0.504151	1.398925	0.435791	0.648194
66.66%	0.240479	0.778809	0.281982	0.137939

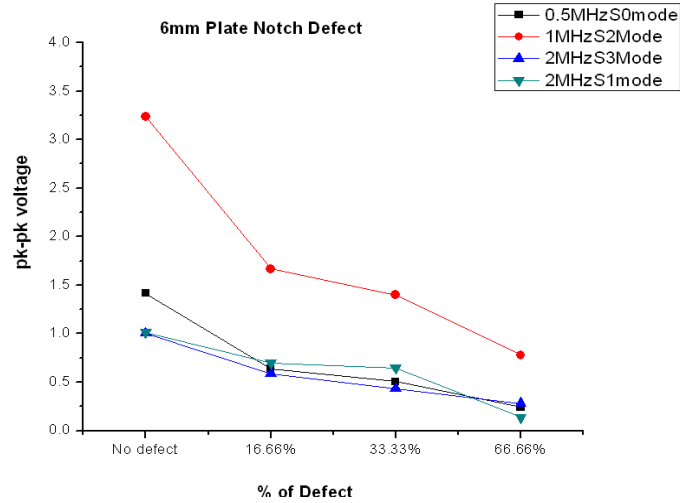


Figure 5.7: Trends of 6mm Plate of Notch Defect with Different Modes

It is very clear that 1MHz S_2 and S_3 modes are most sensitive to the notch defect. 1 MHz S_2 and S_3 mode is highly energized mode and least attenuative mode, the peak to peak voltage amplitude with this mode is higher when compared with other modes. Disperse complemented by which shows that the modes suffers least attenuation in comparison to other modes in 6mm plate. From the DISPERSE, it is clear that the mode S_2 and S_3 is very less attenuate than other mode for 1MHz in 6mm plate as shown in figure 5.3.

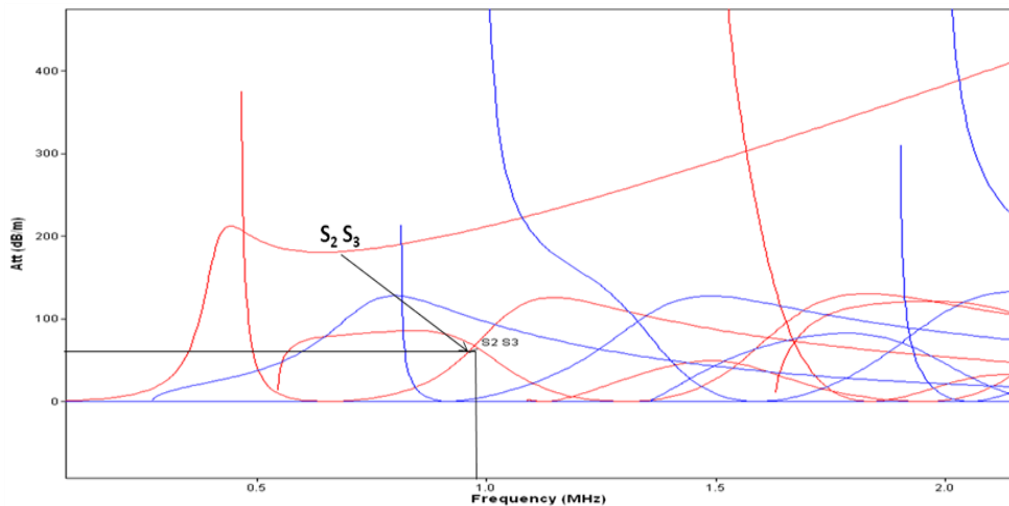


Figure 5.8: Attenuation Curves of 6mm Plate

So 1MHz S_2 and S_3 modes were chosen for the testing of 6mm plate with notch type of defect. Magnitude of notch can be related to the fall in pk – pk voltage amplitude of the received signal (Figure 5.7). The total plate is scanned using 1MHz by arranging the transducer at an angle of 16.5 degrees to excite S_2 and S_3 modes.

Scanning also gives an idea about the severity of damage. A plate was manufactured with 12.5%, 25% and 50% on the same plate and the transducers are moved. As the transducer nears the notch, the pk –pk voltage amplitude drastically falls as shown in boxes in Figure 5.9 falls in amplitude with distance indicate the presence of notch. When there is fall in amplitude in through transmission, the plate is tested with pulse echo technique at every grid point by moving the transducer perpendicularly and the pk –pk voltage amplitudes at every point are plotted as shown in Figure 5.10.

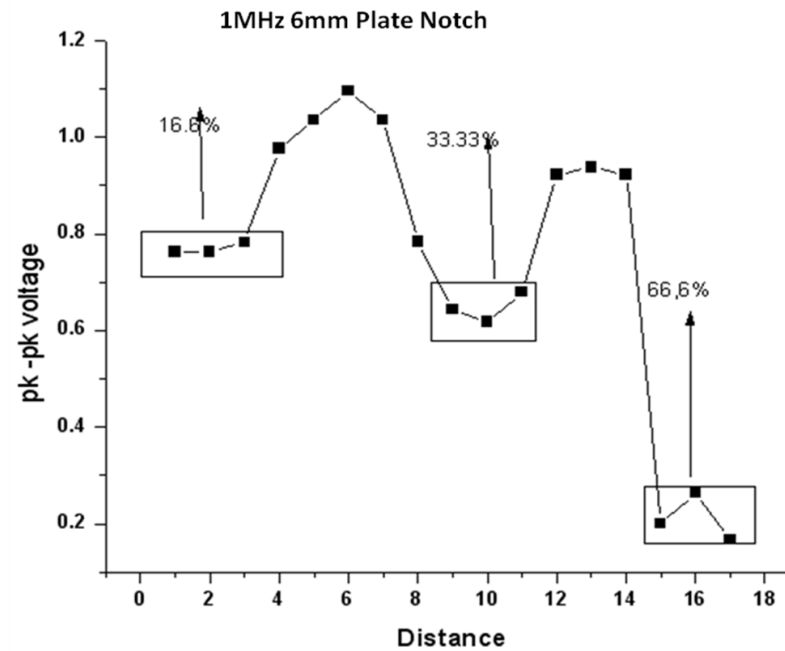


Figure 5.9: Through Transmission of 6mm Plate at grid points

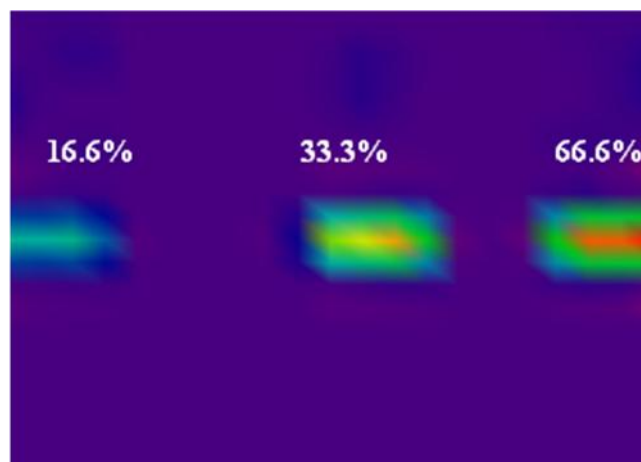


Figure 5.10: Pulse Echo at grid points of 6mm plate With Notch Defect

Table 5.4: pk –pk voltage Pulse Echo Voltage amplitude (V) values at the Defects

	16.66%	33.3%	66.6%
pk –pk Voltage Amplitude(V)	2.62	3.131	3.783

5.2 Testing for Punch Defect

4mm and 6mm plates were manufactured with seeded punch defects.

5.2.1 4mm Plate in water

Steel plate of thickness 4mm has defects of type punch with varying depths. The punch depth is varied from 0.5mm, 1mm, 2mm to simulate 12.5%, 25% and 50% defect as shown in Figure 5.11. This is tested with 0.5MHz, 1MHz and 2MHz with different angles. Out of these angles, only suitable modes were taken for testing. Modes of each frequencies, only few were taken for testing because the rest of modes of different frequencies which gave very weak output signal were and also have less energy to detect the defect on the plate.

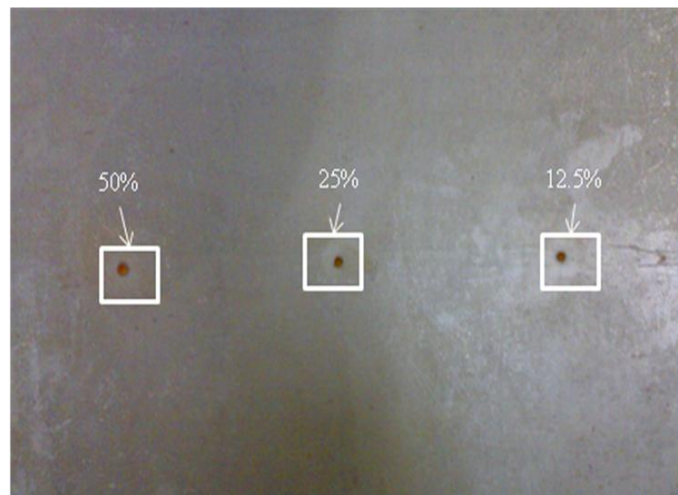


Figure 5.11: 4mm Plate with Punch Defect

Following modes and frequencies were used to excite different modes for 4mm plate with punch defects

- 1 0.5MHz with an angle of 17.4° degrees to excite S_0 mode
- 2 1MHz with an angle of 14.2° to excite S_1 , S_2 and S_3 modes , 16.6° degree to excite A_1 modes and 28.5° to excite S_0 mode.
- 3 2MHz with an angle of 14.7° to excite S_4 mode, 21.6° to excite S_1 , S_2 and S_3 modes.

Table 5.5: pk –pk voltage of 4mm Plate with Punch Defect of all modes

	1MHz			2MHz		0.5MHz
Mode	S ₁ S ₂ S ₃	A ₁	S ₀	S ₄	S ₁ S ₂ S ₃	S ₀
Angle	14.2°	16.6°	28.5°	14.7°	21.6°	17.4°
No defect	3.63	0.318	0.194	1.373	0.645	3.42
12.50%	3.031	0.345	0.168	1.091	0.521	3.35
25%	2.008	0.187	0.152	0.905	0.441	3.31
50%	1.116	0.195	0.108	0.5444	0.261	3.3

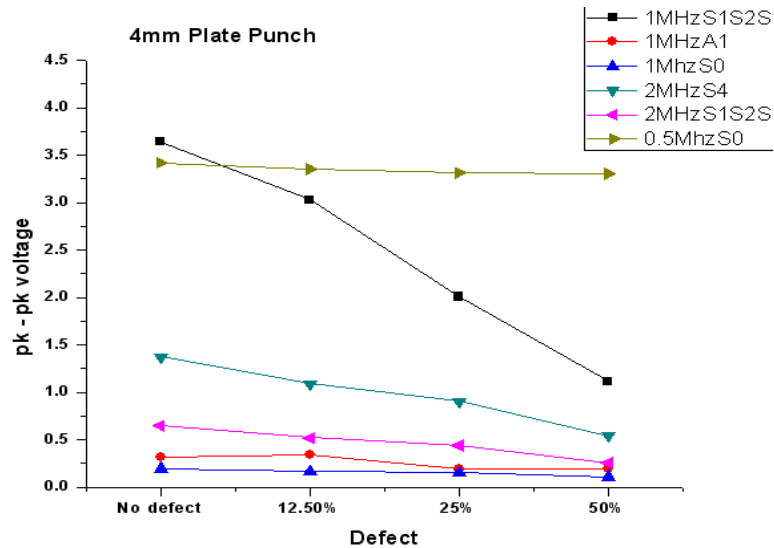


Figure 5.12: Trends of 4mm Plate of Punch Defect with Different Modes

It is very clear that 1MHz S₁, S₂ and S₃ modes are most sensitive to the punch defect. 1MHz S₁, S₂ and S₃ mode is highly energized mode and least attenuative mode, the peak to peak voltage amplitude with this mode is higher when compared with other modes. Disperse complemented by which shows that the modes suffers least attenuation in comparison to other modes in 4mm plate. From the DISPERSE, it is clear that the mode S₁, S₂, S₃ is very less attenuate than other modes for 1MHz in 4mm plate as shown in figure 5.3.

So 1MHz S₁, S₂ and S₃ mode was chosen for the testing of 4mm plate with punch type of defect. Magnitude of notch can be related to the fall in pk – pk voltage amplitude of the received signal (Figure 5.12). The total plate is scanned using 1MHz by arranging the transducer at an angle of 14.2 degrees to excite S₁, S₂ and S₃ mode.

Scanning also gives an idea about the severity of damage. A plate was manufactured with 12.5%, 25% and 50% on the same plate and the transducers are moved. As the

transducer nears the punch, the pk –pk voltage amplitude drastically falls as shown in circles in Figure 5.13 falls in amplitude with distance indicate the presence of punch. When there is fall in amplitude in through transmission, the plate is tested with pulse echo technique at every grid point by moving the transducer perpendicularly and the pk –pk voltage amplitudes at every point are plotted as shown in Figure 5.14.

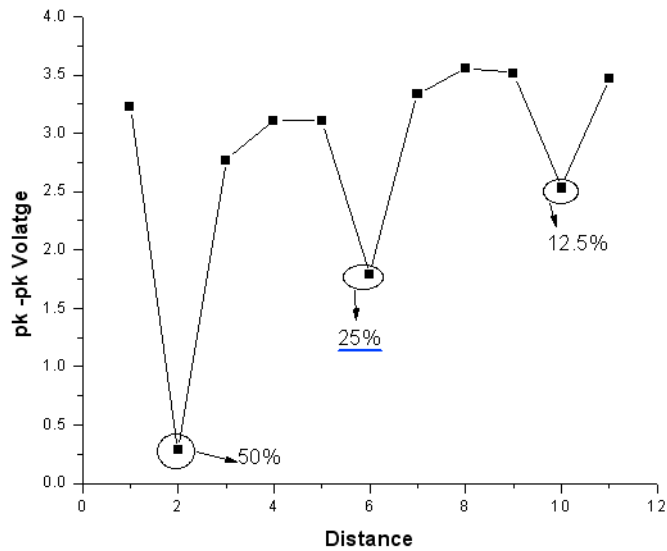


Figure 5.13: Through Transmission of 6mm Plate with Punch Defect at grid points

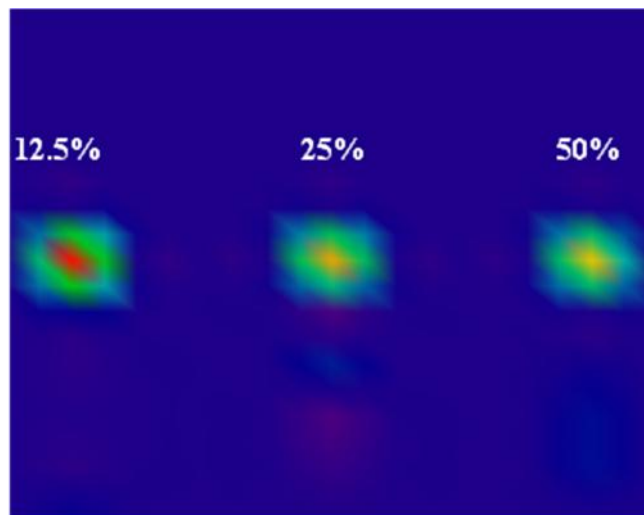


Figure 5.14: Pulse Echo at grid points of 6mm plate With Punch Defect

Table 5.6: pk –pk voltage Pulse Echo Voltage amplitude (V) values at the Defects

	12.5%	25%	50%
pk –pk Voltage Amplitude(V)	1.555	1.58	1.73

5.2.2 6mm Plate in water

Steel plate of thickness 6mm has defects of type punch with varying depths. The punch depth is varied from 1mm, 2mm, 4mm to simulate 12.5%, 50% and 50% defect as shown in Figure 5.15. This is tested with 0.5MHz, 1MHz and 2MHz with different angles. Out of these angles, only suitable modes were taken for testing. Modes of each frequencies, only few were taken for testing because the rest of modes of different frequencies which gave very weak output signal were ignored and also have less energy to detect the defect on the plate.

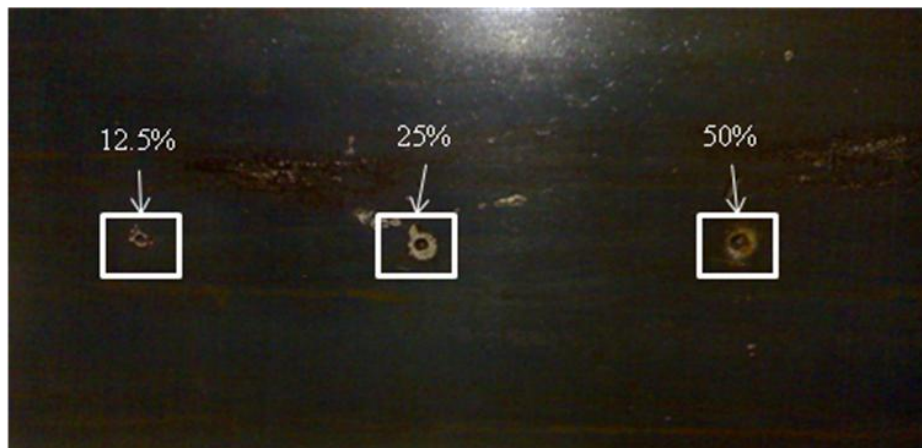


Figure 5.15: 6mm Plate with Punch Defect

Following modes and frequencies were used to excite different modes for 6mm plate with notch defects

- 1 1MHz with an angle of 16.5° to excite S_2 and S_3 modes.
- 2 2MHz with an angle of 27.9° to excite S_2 and S_3 mode, 19.9° to excite S_4 mode and 14.7° to excite S_5 modes.

Table 5.7: pk –pk voltage of 6mm Plate with Punch Defect of all modes

Mode	2MHz			1MHz
	S_5	S_4	$S_2 S_3$	$S_2 S_3$
Angle	14.7°	19.9°	27.9°	16.5°
No Defect	0.900	0.501	1.402	2.104
16.60%	0.509	0.486	0.995	1.631
33.30%	0.284	0.433	0.717	1.419
50%	0.170	0.405	0.576	1.120

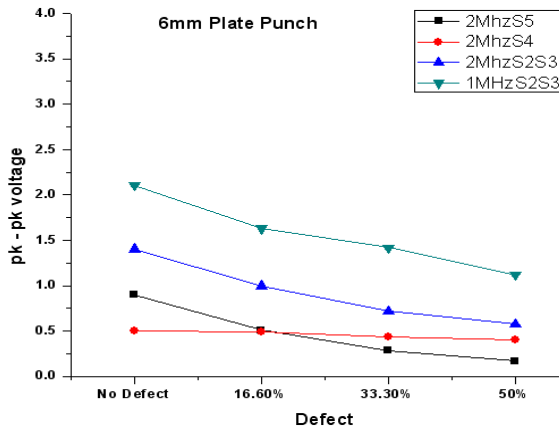


Figure 5.16: Trends of 6mm Plate of Punch Defect with Different Modes

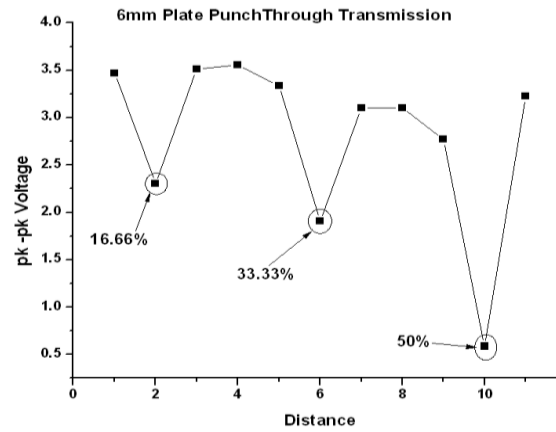


Figure 5.17: Through Transmission of Scanned Plate

It is very clear that 1MHz S_2 and S_3 modes are most sensitive to the punch defect. 1MHz S_2 and S_3 mode is highly energized mode and least attenuative mode, the peak to peak voltage amplitude with this mode is higher when compared with other modes. Disperse complemented by which shows that the modes suffers least attenuation in comparison to other modes in 6mm plate. From the DISPERSE, it is clear that the mode S_1 is very less attenuate than other mode for 1MHz in 6mm plate as shown in figure 5.3.

So 1MHz S_2 and S_3 mode was chosen for the testing of 6mm plate with punch type of defect.

Magnitude of punch can be related to the fall in pk – pk voltage amplitude of the received signal (Figure 5.16). The total plate is scanned using 1MHz by arranging the transducer at an angle of 16.5 degrees to excite S_2 and S_3 mode.

Scanning also gives an idea about the severity of damage. A plate was manufactured with 12.5%, 25% and 50% on the same plate and the transducers are moved. As the transducer nears the punch, the pk –pk voltage amplitude drastically falls as shown in circles in Figure 5.17 falls in amplitude with distance indicate the presence of punch. When there is fall in amplitude in through transmission, the plate is test with pulse echo technique at every grid point by moving the transducer perpendicularly and the pk –pk voltage amplitudes at every point are plotted as shown in Figure 5.18.

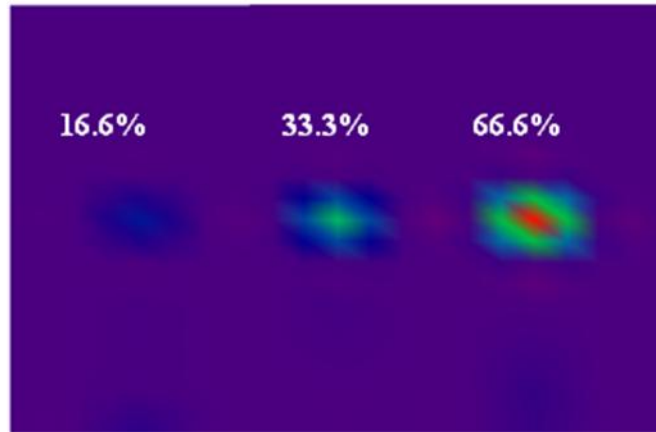


Figure 5.18: Pulse Echo at grid points of 6mm plate With Punch Defect

Table 5.8: pk –pk voltage Pulse Echo Voltage amplitude (V) values at the Defects

	16.6%	33.3%	50%
pk –pk Voltage Amplitude(V)	1.073	1.888	3.359

5.3 Testing for Hole Defect

4mm and 6mm plates were manufactured with seeded hole defects.

5.3.1 4mm Plate in water

Steel plate of thickness 4mm has defects of type hole with varying depths. The hole diameter is varied from 3mm, 6mm, 12mm and 16mm of through and partial hole defect as shown in Figure 5.19. This is tested with 0.5MHz, 1MHz and 2MHz with different angles. Out of these angles, only suitable modes were taken for testing. Modes of each frequencies, only few were taken for testing because the rest of modes of different frequencies which gave very weak output signal were ignored and also have less energy to detect the defect on the plate.

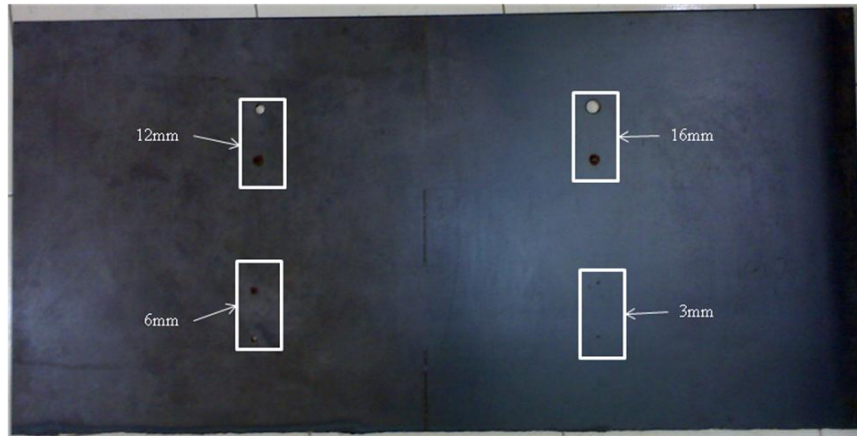


Figure 5.19: 4mm Plate with Holes

Following modes and frequencies were used to excite different modes for 4mm plate with hole defects

- 1 0.5MHz with an angle of 17.4° degrees to excite S_0 mode
- 2 1MHz with an angle of 14.2° to excite S_1, S_2 and S_3 modes, 16.6° to excite A_1 modes.
- 3 2MHz with an angle of 14.7° to excite S_4 mode.

By using 0.5MHz, 1MHz and 2MHz with different angles the defects are tested at same settings to know the trend of each mode to change in defect level.

Table 5.9: pk -pk voltage of 4mm Plate with Hole Defect of all modes

	0.5MHz		1MHz				2MHz			
MODE	S_0		A_1		$S_1 S_2 S_3$		S_4		S_0	
ANGLE	17.4°		16.6°		14.2°		14.7°		30°	
Diameter	Through	Partial	Through	Partial	Through	Partial	Through	Partial	Through	Partial
0mm	3.72	3.72	2.45	2.45	3.38	3.38	1.09	1.09	1.13	1.13
3mm	3.65	3.74	2.02	2.29	2.78	2.33	0.72	0.94	0.79	0.91
6mm	3.45	3.55	1.63	1.90	2.47	2.27	0.495	0.84	0.44	0.79
12mm	3.007	3.50	1.372	1.78	1.545	1.81	0.4	0.53	0.424	0.78
16mm	2.781	3.00	0.803	1.64	0.959	1.48	0.344	0.53	0.354	0.45

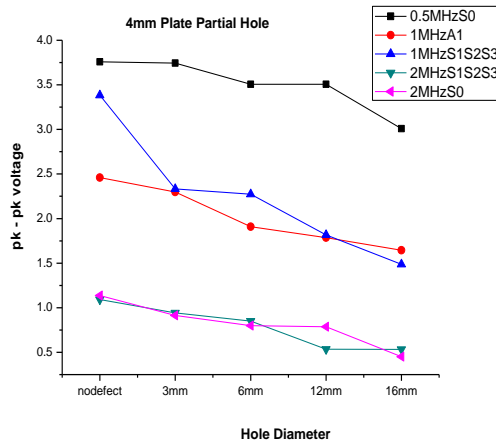


Figure 5.20: 4mm Plate with Partial Holes

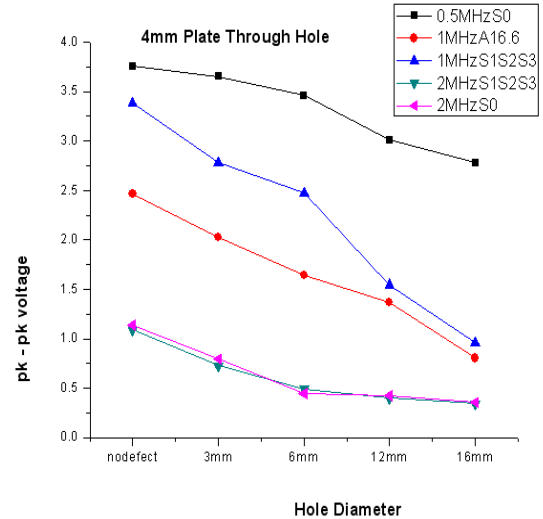


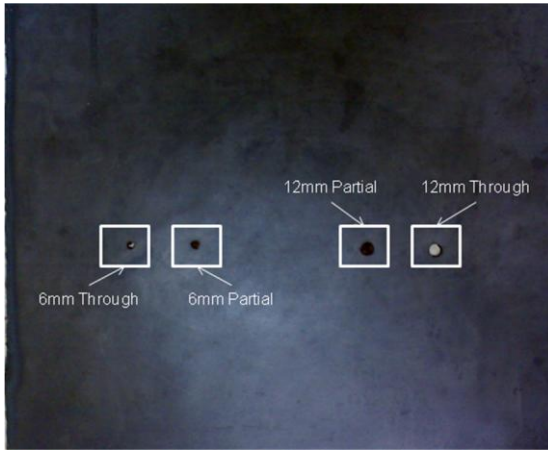
Figure 5.21: 4mm Plate with Through Holes

It is very clear that 1MHz S_1 , S_2 and S_3 modes are most sensitive to the notch defect. 1MHz S_1 , S_2 and S_3 mode is highly energized mode and least attenuative mode, the peak to peak voltage amplitude with this mode is higher when compared with other modes. Disperse complemented by which shows that the modes suffers least attenuation in comparison to other modes in 4mm plate. From the DISPERSE, it is clear that the mode S_1 , S_2 and S_3 is very less attenuate than other mode for 1MHz in 4mm plate as shown in figure 5.3.

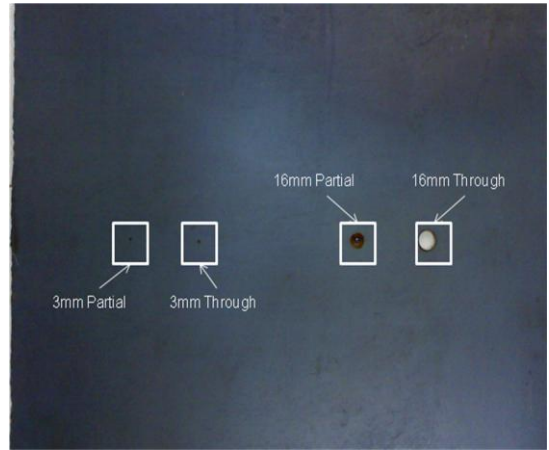
So 1MHz S_1 , S_2 and S_3 mode was chosen for the testing of 4mm plate with hole type of defect.

Magnitude of notch can be related to the fall in pk – pk voltage amplitude of the received signal (Figure 5.20). The total plate is scanned using 1MHz by arranging the transducer at an angle of 14.2 degrees to excite S_1 , S_2 and S_3 mode.

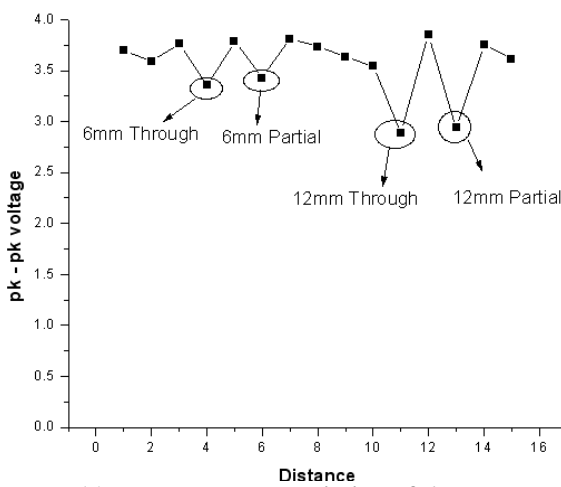
Scanning also gives an idea about the severity of damage. A plate was manufactured with 3mm, 6mm, 12mm and 16mm diameter hole of through and partial on the same plate and the transducers are moved. As the transducer nears the hole, the pk –pk voltage amplitude drastically falls as shown in circles in Figure 5.22(c) and (d) falls in amplitude with distance indicate the presence of hole When there is fall in amplitude in through transmission, the plate is test with pulse echo technique at every grid point by moving the transducer perpendicularly and the pk –pk voltage amplitudes at every point are plotted as shown in Figure 5.22(e) and (f).



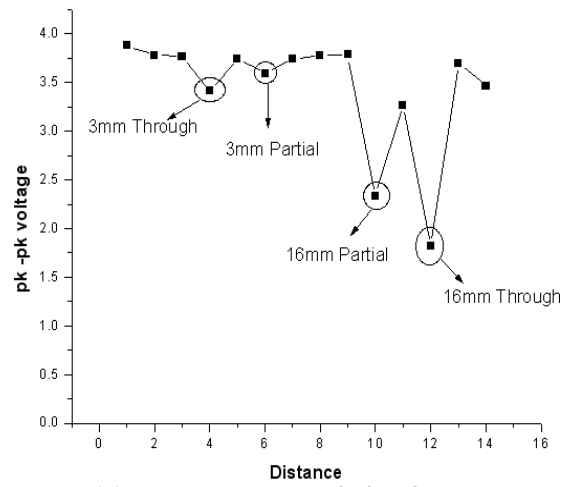
(a) Plate with 6mm and 12mm Holes



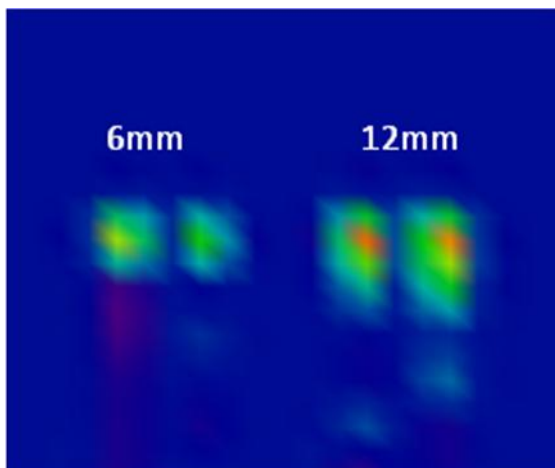
(b) Plate with 3mm and 16mm Holes



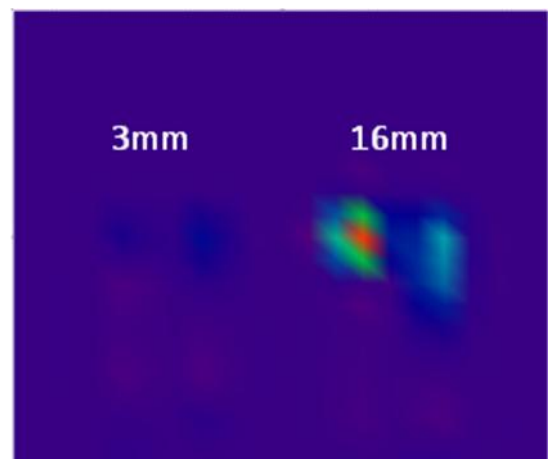
(c) Through Transmission of 6mm and 12mm holes



(d) Through Transmission 3mm and 16mm holes



(e) Pulse Transmission values at grid points of 6mm and 12mm holes



(f) Pulse Transmission values at grid points of 3mm and 16mm holes

Figure 5.22: pk -pk voltage Pulse Echo and Through Transmission Graphs

5.3.2 6mm Plate

Steel plate of thickness 6mm has defects of type hole with varying depths. The hole diameter is varied from 3mm, 6mm, 12mm and 16mm of through and partial hole defect as shown in Figure 5.23. This is tested with 0.5MHz, 1MHz and 2MHz with different angles. Out of these angles, only suitable modes were taken for testing. Modes of each frequencies, only few were taken for testing because the rest of modes of different frequencies which gave very weak output signal were ignored and also have less energy to detect the defect on the plate.

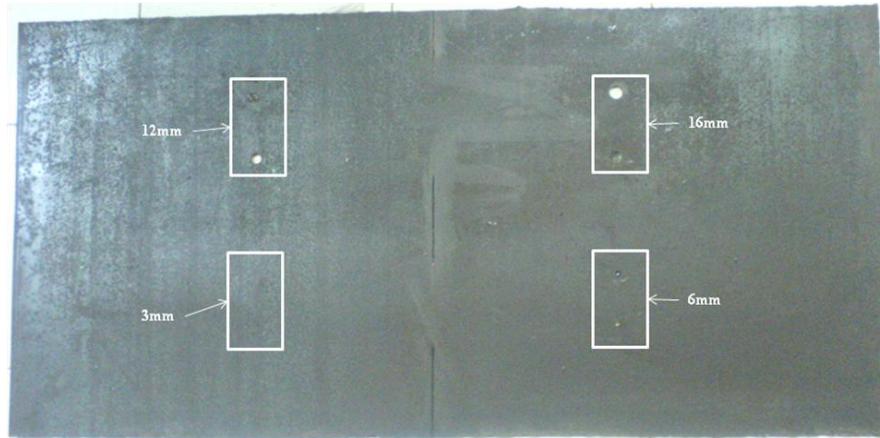


Figure 5.23: 6mm Plate with Holes

Following modes and frequencies were used to excite different modes for 6mm plate with hole defects

- 1 0.5MHz with an angle of 25.77° degrees to excite S_0 mode
- 2 1MHz with an angle of 30° to excite S_0 mode and 16.5° to excite S_2 and S_3 modes.
- 3 2MHz with an angle of 27.9° to excite S_2 and S_3 modes.

Table 5.10: pk –pk voltage of 6mm Plate with Hole Defect of all modes

Mode	1MHz		2MHz				0.5MHz	
	S_1	S_2 S_3	S_2 S_3		S_5		S_0	
Angle	16.5°		27.9°		14.7°		25.77°	
%Defect	Through	Partial	Through	Partial	Through	Partial	Through	Partial
0%	2.653	2.653	1.877	1.877	0.966	0.966	1.798	1.798
3mm	2.067	2.476	0.888	1.477	0.903	0.938	1.375	1.774
6mm	1.300	1.363	0.784	1.402	0.535	0.705	1.141	0.871
12mm	1.031	1.256	0.847	1.145	0.478	0.627	0.491	0.620
16mm	0.737	1.184	0.457	1.099	0.463	0.449	0.533	0.579

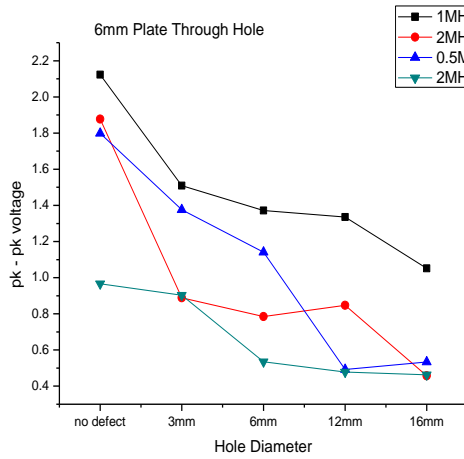


Figure 5.24: 6mm Plate Through Holes Trends

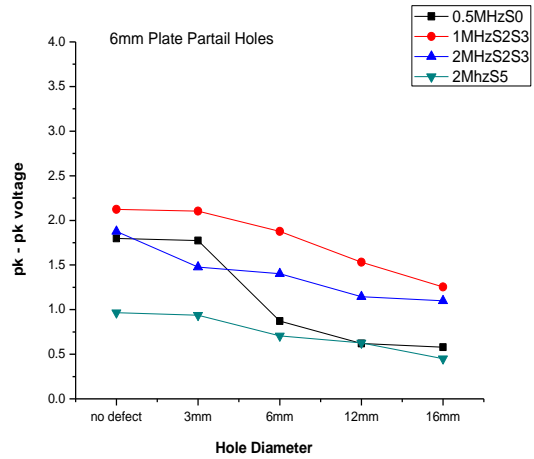


Figure 5.25: 6mm Plate Partial Holes Trends

It is very clear that 1MHz S_1 , S_2 and S_3 modes are most sensitive to the notch defect. 1MHz S_1 , S_2 and S_3 mode is highly energized mode and least attenuative mode, the peak to peak voltage amplitude with this mode is higher when compared with other modes. Disperse complemented by which shows that the modes suffers least attenuation in comparison to other modes in 6mm plate. From the DISPERSE, it is clear that the mode S_1 , S_2 and S_3 is very less attenuate than other mode for 1MHz in 6mm plate as shown in figure 5.3.

So 1MHz S_1 , S_2 and S_3 mode was chosen for the testing of 6mm plate with hole type of defect.

Magnitude of notch can be related to the fall in pk – pk voltage amplitude of the received signal (Figure 5.24). The total plate is scanned using 1MHz by arranging the transducer at an angle of 16.5 degrees to excite S_1 , S_2 and S_3 mode.

Scanning also gives an idea about the severity of damage. A plate was manufactured with 3mm, 6mm, 12mm and 16mm diameter hole of through and partial on the same plate and the transducers are moved. As the transducer nears the hole, the pk –pk voltage amplitude drastically falls as shown in circles in Figure 5.26 (c) and (d) (1-2-3) falls in amplitude with distance indicate the presence of hole. When there is fall in amplitude in through transmission, the plate is test with pulse echo technique at every grid point by moving the transducer perpendicularly and the pk –pk voltage amplitudes at every point are plotted as shown in Figure 5.26 (e) and (f).

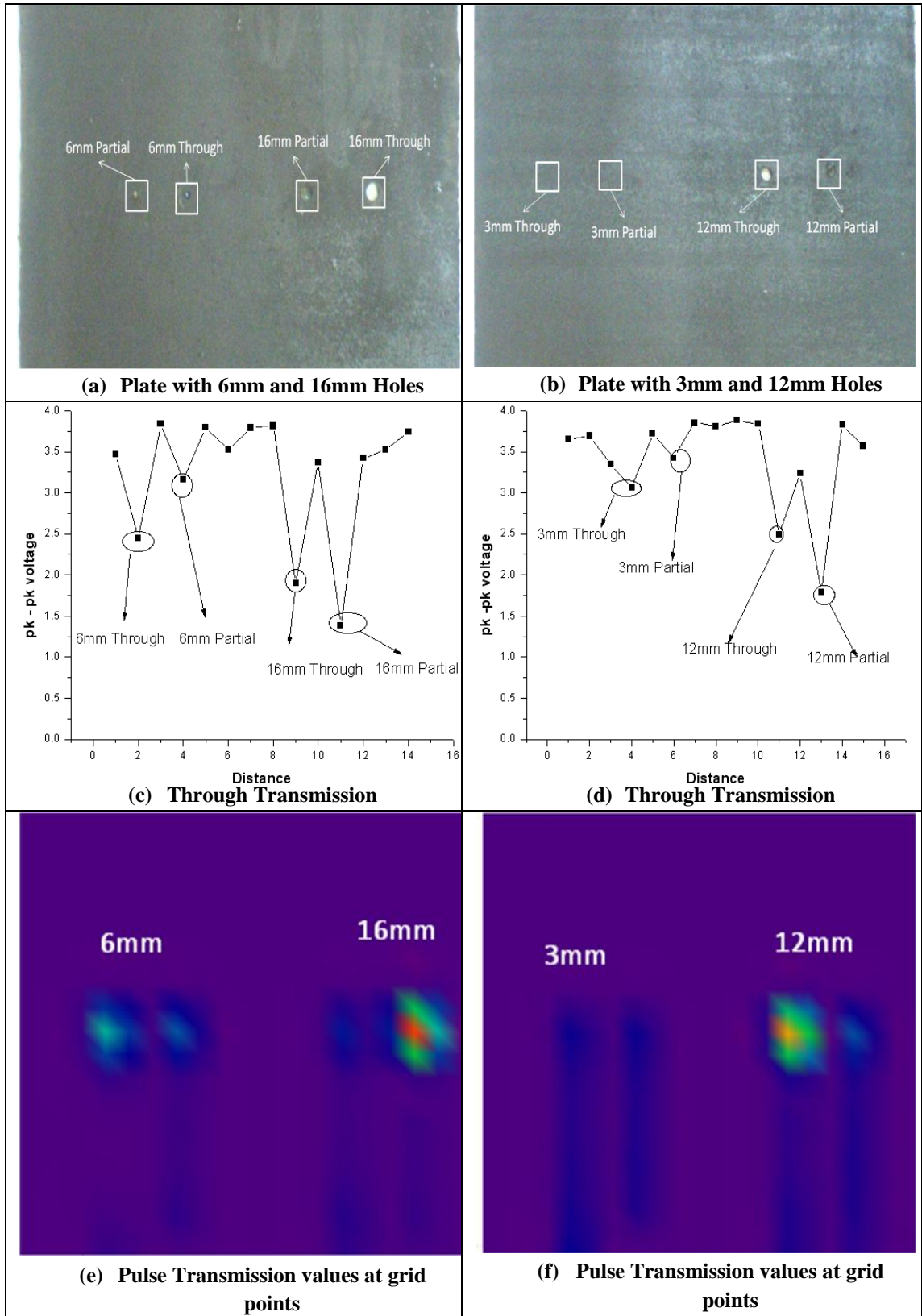


Figure 5.26: pk -pk voltage Pulse Echo and Through Transmission Graphs

The experimental study carried out on plates with seeded notch, punch and hole defect shows that ultrasonics are capable of detecting the mentioned damages. Different modes at different frequencies are sensitive to different type of defects. Following conclusions are drawn from the study.

6.1 Plates in Air

- Presence of damage is indicated by the appearance of a peak between the initial pulse and back wall echo in pulse echo testing of plate specimen in air
- Location of damage is calculated by using the formula $D=VT/2$, where velocity (V) of ultrasonic wave in the plate is known and time of flight is obtained from the pulse echo method.
- Severity of damage is assessed by relative drop of peak to peak voltage ratio as the percentage of damage increases

Excitation of multiple modes, scattering of waves and merging up of signals are the Problems faced in testing of plates in air. So the Testing was carried out by immersing the plates in water.

6.2 Plates immersed in water

- Using water as couplant, most of noise signals are vanished.
- Particular modes sensitive to different defects can be generated by varying the angle of excitation.
- For plates with notch defects S2 S3 modes of frequency 1MHz was found to be most sensitive. Scanning was done using Pulse echo and through transmission to find the location and magnitude of the notch in the plate.
- For plates with hole defects S2S3 modes of frequency 1MHz was found to be most sensitive. Scanning was done using Pulse echo and through transmission to find the location and magnitude of the hole in the plate.
- For plates with punch defects S2S3 modes of frequency 1MHz was found to be most sensitive. Scanning was done using Pulse echo and through transmission to find the location and magnitude of the punch in the plate.

Future Scope of Work

The area of nondestructive testing and damage detection constitutes the extremely important and challenging area of study where wave propagation provides an efficient means of characterizing defects in structures. As the topic of wave propagation is very wide spread and has utilities in many areas of human endeavor, there is much scope for future work.

The experimentation carried out can be extended for:

- Water on one side of the plate to model real life problem of ship hulls..
- Sensitivity and selection of ideal modes for various other manufacturing defects like welding, bending etc can be explored.
- Detection of multiple cracks in steel plates.
- Geometry of plates can be another extension of work in which curved geometry as present in ship hulls etc can be explored.

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