FEASIBILITY OF USING ULTRASONIC GUIDED WAVES FOR UNDER WATER PIPE INSPECTION

A dissertation report submitted in partial fulfillment of the requirements for the award of degree of

Master of Engineering
In
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Submitted By
GAGANDEEP SINGH MAVI
Roll No 801181012

Under Guidance of:

Mr. Sandeep K. Sharma
Assistant Professor, MED
Thapar University, Patiala

DEPARTMENT OF MECHANICAL ENGINEERING
THAPAR UNIVERSITY
PATIALA-147004, INDIA
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CERTIFICATE

I hereby certify that the work which is presented in this dissertation report entitled "**Feasibility of using ultrasonic guided waves for under water pipe inspection**" in partial fulfillment of requirement for the award of the degree in "**Masters of Engineering In CAD/CAM & ROBOTICS**" submitted in the Department of Mechanical Engineering, Thapar University, Patiala, is an authentic record of the review carried out by him under the supervision of **Mr. Sandeep K. Sharma, Assistant Professor, MED, Thapar University, Patiala.**

The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

Gagandeep Singh Mavi

Dated: 17 July 2013 (Gagandeep Singh Mavi)

This is to certify that above declaration made by the student concerned is correct to the best of my knowledge and belief.

Mr. SANDEEP K. SHARMA

Assitant Professor,

Department of Mechanical Engineering

Thapar University,

Patiala- 147004

Countersigned By:

Dr. AJAY BATISH

Professor and Head,

Department of Mechanical Engineering,

Thapar University,

Patiala- 147004

Dr. S.K.MOHAPATRA

Dean of Academic Affairs,

Thapar University,

Patiala- 147004

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(Gagandeep Singh Mavi)

Reg.No: 801181012

ABSTRACT

Non destructive testing techniques are preferred techniques for damage detection in this new era of development. Health monitoring of materials and structures during its service life using NDT is an emerging field. Ultrasonic testing is a promising candidate of NDT. It uses high frequency sound waves which are injected into the material to detect the defects and discontinuities in the material. This report presents the study of feasibility of using pulse transmission (PT) method with ultrasonic guided waves to detect the simulated defects in immersed pipes.

Mild steel pipe specimens in immersed condition have been used in the study. Presence of water in immersed state has been exploited as a means to couple the transducer with the pipe. A conventional ultrasonic system consisting of pulser/receiver and data acquisition system has been used. Attenuation of the transmitted signal has been used as an indicator to measure the presence and extent of damage. Actual corrosion has been induced in the pipes using impressed anodic current technique. Ultrasonic signatures recorded at different stages of corrosion have been found to relate with extent of material loss due to corrosion

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INTRODUCTION

MOTIVATION

Pipes have been used in the industries for carrying fluids, gases and slurries. In many oil and gas refineries, chemical plants, fertilizers plants and power plants long pipelines are used in transportation of chemicals and oil. These pipelines carry hazardous chemicals and gases, any leakage or rapture can lead to unsafe situation. Due to unhealthy environment these pipes are more prone to defects like corrosion. Usually these pipelines are buried under ground so it is not possible to inspect damages visually in long pipes. The presence of flaws and corrosion in pipes is one of the major problems in industries and civil plants. Hence, these pipelines need to be monitored periodically to assess the damage before any failure occurs.

In order to meet this need, the discipline of Structural Health Monitoring (SHM) has been emerged. Using non destructive testing (NDT) the damages in pipes can be easily detected. Ultrasonic testing is one of the significant NDT methods to monitor the defects in long range pipes. It involves the application of wave propagation in material (pipe) and aims to assist engineers in realizing the benefits of structural health monitoring. Health of these structures is monitored by recording propagation of stress waves through them. The wave characteristics changes due to deterioration in the pipes. Also waves are sensitive to the extent and character of damage.

Mild steel pipe specimens in immersed condition have been used in the study. Testing has been done to detect the notch, hole and corrosion defects by using ultrasonic guided waves.

1.1 STRUCTURAL HEALTH MONITORING

The process of implementing a damage detection and characterization strategy for engineering structures is referred to as Structural Health Monitoring (SHM). The subject of structural health monitoring (SHM) is emerging as an increasingly important component of overall Non-destructive Evaluation (NDE) programs and is now being considered for implementation in a variety of applications including spacecraft components, bridges, and aircraft. Over the past several years, there have been a number of limited demonstrations of SHM in actual field applications. In addition to the Army, Navy and Air Force, other federal agencies interested in this topic include the Federal Aviation Administration, NASA and the department of Transportation. The detection of damage at any location is a common challenge in most large structures, and thus SHM has potential applications across a range of industrial sectors. Successful field implementation of SHM has not been widely achieved and depends on overcoming several roadblocks including the development and demonstration of SHM sensors that have long term stability and reliability, validation of the capability of the SHM systems in terms of the probability of detection of flaws, and finally the integration of the SHM system results into structural and platform maintenance strategies. An increasing number of efforts are focusing on identifying these implementation issues and developing solutions for them.

It is usually performed for one or more of the following three reasons.

1) Damage Detection

This is perhaps the most obvious and common reason. The structure is continuously monitored and any changes in its response are noted. The aim is to make a rapid and accurate assessment the safety of a structure following an event, such as an earthquake, without requiring a dangerous and expensive manual inspection.

2) Long Term Monitoring for Deterioration

This differs from damage detection in that it aims to detect changes in a structure that take place over many years. The aim here is to be assured of the structural performance and continued value of the asset under "normal" conditions.

3) Determine "As Built" Structural Properties

A short term monitoring program can be used to determine the actual dynamic properties of a structure. These can be used by the designers to compare with design values to verify design assumptions. Ambient or forced vibrations can be used to determine these properties at different levels of motion.

1.2 NON DESTRUCTIVE TESTING (NDT)

Nondestructive testing is defined by the American Society for Nondestructive Testing (ASNT) as: “The determination of the physical condition of an object without affecting that object’s ability to fulfill its intended function. Nondestructive testing techniques typically use a probing energy form to determine material properties or to indicate the presence of material discontinuities (surface, internal or concealed). Non-destructive examination (NDE), non-destructive inspection (NDI), and non-destructive evaluation (NDE) are also expressions commonly used to describe this technology. Although NDT cannot guarantee that failures will not occur, it plays a significant role in minimizing the possibilities of failure. As a part of "safe life" design, it was intended that a structure should not develop macroscopic defects during its life, with the detection of such defects being a cause for removal of the component from service. In response to this need, increasingly sophisticated techniques using ultrasonic, eddy currents, x-rays, dye/Penetrant, magnetic particles and other forms of interrogating energy emerged.

1.2.1 History of NDT

Non-destructive testing has been practiced for many decades, with initial rapid developments in instrumentation spurred by the technological advances that occurred during World War II and the subsequent defense effort. Huge accidents (like exploding of boilers in industry or in ships or rail accidents) during 19th and 20th century resulted in early rapid developments in NDT techniques. During the earlier days, the primary purpose was the detection of defects. Mainly two events occurred which caused a major change in the NDT field. First, improvements in the technology led to the ability to detect small flaws, which caused more parts to be rejected even though the probability of component failure had not changed. However, the discipline of fracture mechanics emerged, which enabled one to predict whether a crack of a given size will fail under a particular load when a material's fracture toughness properties are known. Other laws were developed to predict the growth rate of cracks under cyclic loading (fatigue). With the advent of these tools, it became possible to accept structures containing defects if the sizes of those defects were known. This formed the basis for the new philosophy of “damage tolerant" design. Components having known defects could continue in service as long as it could be established that those defects would not grow to a critical, failure producing size. A new challenge was thus presented to the non-destructive testing community. Detection was not enough. One needed to also obtain quantitative information about flaw size to serve as an input to fracture mechanics based predictions of remaining life. The need for quantitative information was particularly strong in the defense and nuclear power industries and led to the emergence of quantitative non-destructive evaluation (QNDE) as a new engineering/research discipline.

1.3 DIFFERENCE BETWEEN NON DESTRUCTIVE AND DESTRUCTIVE TESTING

Destructive testing has been defined as a form of mechanical test (primarily destructive) of materials whereby certain specific characteristics of the material can be evaluated quantitatively. In some cases, the test specimens being tested are subjected to controlled conditions that simulate service. The information that is obtained through destructive testing is quite precise, but it only applies to the specimen being examined. Since the specimen is destroyed or mechanically changed, it is unlikely that it can be used for other purposes beyond the mechanical test. Such destructive tests can provide very useful information, especially relating to the material's design considerations and useful life. Destructive testing may be dynamic or static and can provide data relative to the following material attributes:

- Ultimate tensile strength
- Proof stress
- Ductility
- Elongation characteristics
- Fatigue strength
- Corrosion resistance
- Creep strength
- Hardness
- Reduction of area

Other than the fact that the specimen being examined typically cannot be used after destructive testing for any useful purpose, it must also be stressed that the data achieved through destructive testing are specific to the test specimen only.

1.3.1 Benefits of destructive testing

In different fields of engineering destructive testing is used. Some of the advantages of using destructive testing are:

- Reliable and accurate data from the test specimen.
- Extremely useful data for design purposes.
- Information can be used to establish standards and specifications.
- Data achieved through destructive testing is usually quantitative.
- Typically, various service conditions are capable of being measured.
- Useful life can generally be predicted.

1.3.2 Limitations of destructive testing

For many reason destructive testing is performed less these days. Some of which are as follows:

- Data applies only to the specimen being examined.
- Most destructive test specimens cannot be used once the test is complete.
- Many destructive tests require large, expensive equipment in a laboratory environment.

1.3.3 Benefits of nondestructive testing

Using nondestructive testing one can save the material from damaging. Benefits of using NDT are as follows:

- The part is not changed or altered and can be used after examination.
- Every item or a large portion of the material can be examined with no adverse consequences.
- Materials can be examined for conditions internal and at the surface.
- Parts can be examined while in service.
- Many NDT methods are portable and can be taken to the object to be examined.
- Nondestructive testing is cost effective.

1.3.4 Limitations of nondestructive testing

As it depend on different conditions which method is useful. So limitations of using NDT are:

- It is usually quite operator dependent.
- Some methods do not provide permanent records of the examination.
- NDT methods do not generally provide quantitative data.

- Orientation of discontinuities must be considered.
- Evaluations of some test results are subjective and subject to dispute.
- While most methods are cost effective, some, such as radiography, can be expensive.
- Defined procedures that have been qualified are essential.

In conclusion, there are obvious benefits for requiring both nondestructive and destructive testing. Each is capable of providing extremely useful information, and when used jointly can be very valuable to the designer when considering useful life and application of the part.

1.4 DEFECTS IN MATERIALS

Any local variation in material continuity such as change in geometry, structure, composition or properties or presence of holes, cavities or cracks is known as discontinuity and when any discontinuity single or multiple, is of such size, shape, type and location that it creates a chance of material failure in service, it is called defect. Finding defects is one the most frequent objectives of NDT. The purpose of NDT is to locate various flaws in materials and products. Let us now go through in brief the most common defects caused in materials

1) **Casting defects** – Casting is the process of causing liquid metal to fill a cavity or a mould and solidifies into a useful shape. The flaws which may be formed during the above solidification process are:

- Shrinkage flaw
- Cold shut (shrink crack)
- Stress crack
- Blow holes

2) Forging defects –Forging is working of metals into useful shape by hammering or pressing. Most forging operations are carried out hot, although certain metals can be cold forged. Defect that occur during forging are

- Forging cracks
- Forging lap
- Blow holes

3) Welding defects- Welding is process of joining metals in which the pieces to be joined are bound with alloying taking place at interface. Possible defects that can occur are listed below

- Crater crack
- Stress crack
- Porosity
- Undercut (groove)

4) Corrosion defects-. Corrosion is the deterioration of materials by chemical action of some surroundings or contacting medium, which may be liquid, gas or combination of two.defects due to corrosion are

- Reduce amount of material
- Small cracks
- Holes

Defects caused in materials are mainly cracks, holes and severe damages can also be done by corrosion. The presence of flaws and corrosion in pipes is one of the major problems in industrial and civil plants, as these pipes take water, oil, steam and gas. So, present study will use NDT technique for the detection of defects like notch, holes and corrosion in cylindrical geometries.

1.5 NONDESTRUCTIVE TESTING METHODS

The aim of all NDT techniques is to detect and locate defects, without causing any damage to the component under inspection. Various NDT methods which can be used for testing and inspecting defects of an object

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

Some of the commonly used NDT techniques are as follows:

1.5.1Visual and Optical Testing (VT): Most widely used of all NDT techniques is visual testing and is the oldest of them. Although it is not possible to quantify the observation made, it is very important that all inspection include preliminary visual check during which abnormal conditions such as high wear, corrosion, erosion, impact damage, distortion, discoloration, missing parts etc. can be noted. Based on these findings, the course of further inspection is generally decided. In quality control, as well as in maintenance operations, visual testing is the first line of defense. When deciding upon whether to use visual testing, it is important to understand its potential as well as its limitations. If the visual method is not sufficient for the problem at hand, more complex methods must be considered. Using the visual inspection method for enclosed systems can be challenging and possibly ineffective. To enable a technician or engineer to inspect these difficult-to-see areas, a device known as a borescope is often used. Borescopes are essentially miniaturized cameras that can be placed on the end of a fiber optic cable. The camera can then be inserted into regions that are obstructed from direct visual inspection, and the resulting images are viewed in real-time on a video screen by the inspector.

1.5.2 Radiography Testing (RT): Radiography is NDT method based on the principle of differential absorption of pentrating radiation by object under test. Owing to the varying characteristics or composition of the structure of the test object, different portions absorb different amounts of penetrating radiation. The radiation passing through without being absorbed is recorded on a film and viewed on an illuminated screen. The picture thus seen is used to locate defects in the test object. Early literature notes the ability of radiographs to detect discontinuities in castings, forgings, and welds in metals. Discontinuities such as pores or inclusions in metals are readily detected in many cases. Cracks and holes may also be detected using radiographic techniques as shown in figure.1.1, but attention must be paid to orientation and residual stress issues. Radiography continues to be widely used despite the expense and safety implications of the equipment.

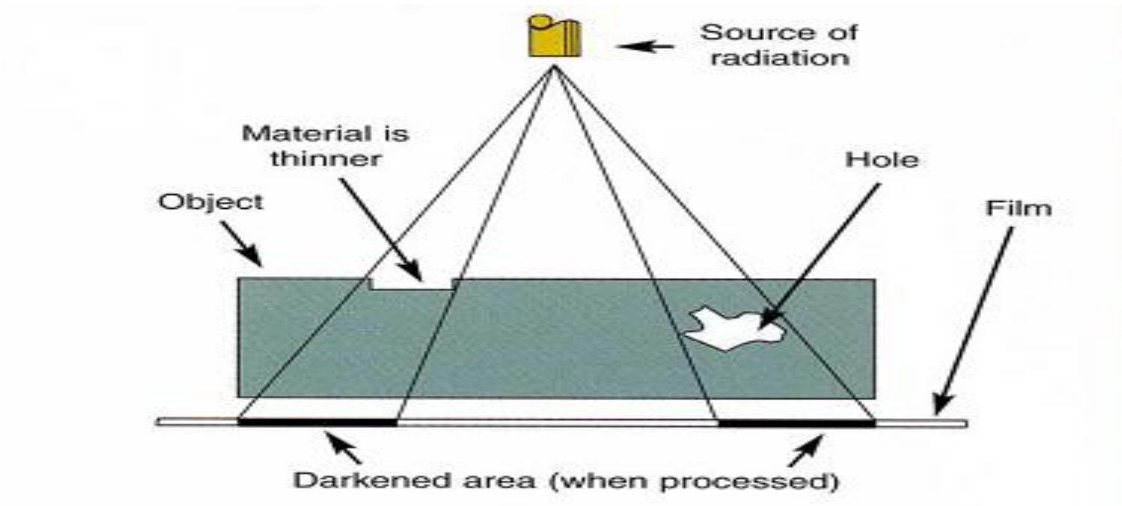


Figure 1.1: Radiography Testing Method [1]

1.5.3 Electromagnetic Testing (ET): when a moving or changing magnetic field passes through a conducting material, it induces a current in it. A magnet pulled across a sheet of copper or aluminum will produce irregular current flow, inducing whirlpools very similar to those found in wake of ship. These turbulent and irregular electrical currents are called eddy currents. Though these currents are random in nature they produce their own magnetic field which creates dragging force between the plate and the magnet. Any change in the material or geometry can be detected by the excitation coil as a change in the coil impedance. The simplest coil comprises a ferrite rod with several turns of wire wound at one end and which is positioned close to the surface of the product to be tested. When a crack, for example in **Figure1.2**, occurs in the product surface the eddy currents must travel farther around the crack and this is detected by the impedance change. Coils can also be used in pairs, generally called a driven pair, and this arrangement can be used with the coils connected differentially.

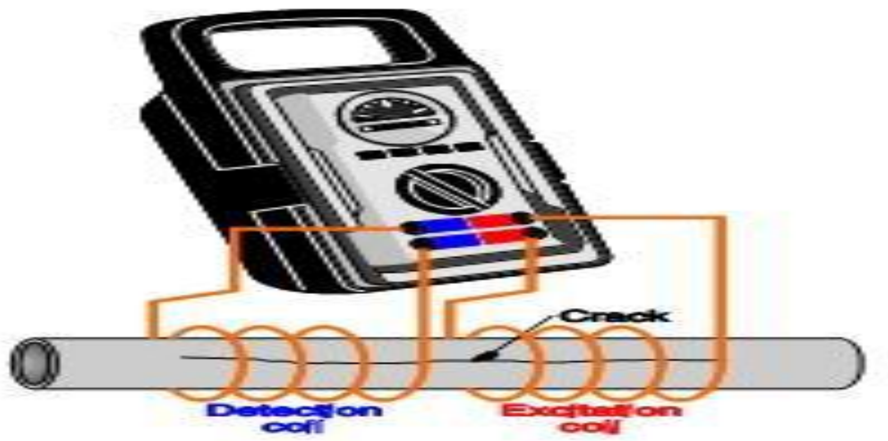


Figure 1.2: Eddy Current Testing Method [2]

1.5.4 Ultrasonic Testing (UT): In this inspection technique, high frequency sound waves are sent into the object under test. The sound wave travel through the material as shown in **Figure 1.3.** During their path of travel they suffer loss of energy and are reflected at interfaces. A receiver probe picks up the reflected wave and analysis of the signal is done to locate flaws in object under inspection. Sound waves follow laws of optics in their propagation. Further velocity of propagation of sound in various metals has been very accurately detected. This technique often used for thickness measurements and crack detection. Recent advances in ultrasonic techniques have largely been in the field of phased array ultrasonic, now available in portable instruments. 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. These testing can be used for detecting various surface as well as internal defects.

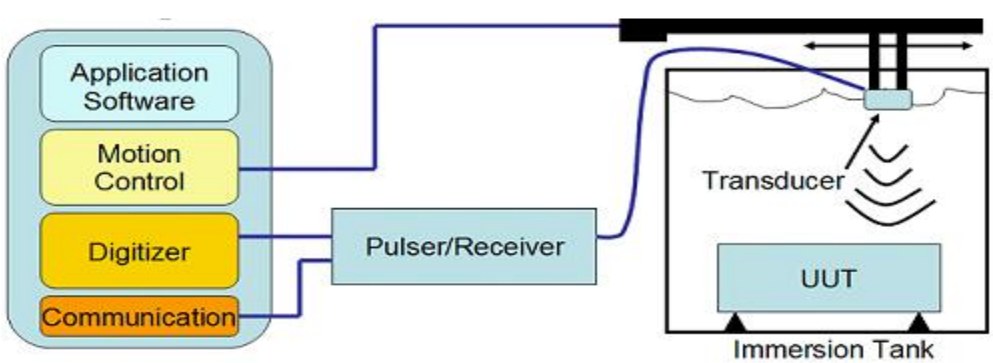


Figure 1.3: Ultrasonic Testing Method [2]

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

1.5.6Magnetic Particle Testing (MT): Magnetic particle testing is a very useful method for detection of surface and sub surface cracks in ferrous material components. In this method when the part is being inspected is first magnetized, there is flow of magnetic lines of force on the portion under test. At this stage, magnetic powder is sprayed on the surface. If there is any discontinuity or flaw in the surface the flow of lines interrupted and intermediate poles are induced at either side the discontinuity. These inter poles attract the sprinkled magnetic powder. The image is more sharp if the flaw is closer to the surface. One thing kept in mind during magnetic particle testing is the discontinuities parallel to the lines of magnetic force will not show any indication as shown in **Figure1.5.** This phenomenon is familiar to almost everyone from childhood experiments with magnets and iron filings. Magnetic particle techniques thus allow the detection of surface-breaking cracks in steel objects of complex geometry which typically is a challenge for RT methods.

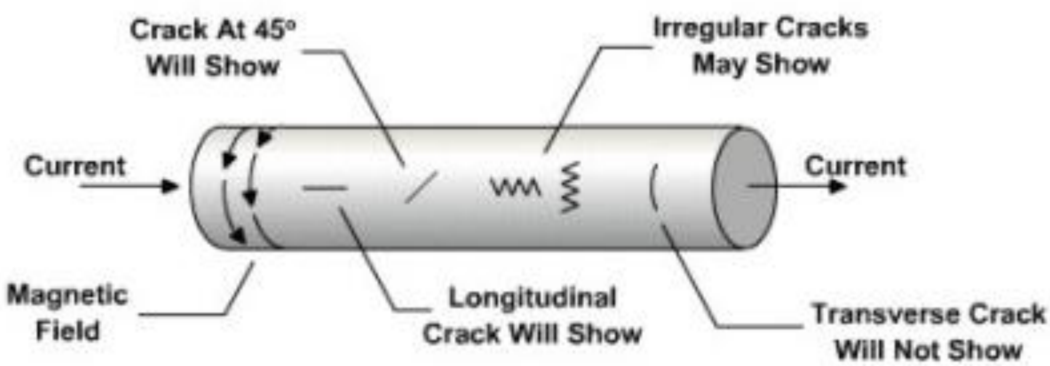


Figure 1.4: Magnetic Particle Testing Method [2]

1.5.7Acoustic Emission Testing (AT): Acoustic emission methods rely on the use of passive sensors to "listen" for mechanical disturbances caused by various degradation processes in test objects. In principle the AE method is very simple figure 1.6, but in practice it can be difficult to separate the vibrations caused by normal in-service processes from those associated with degradation and damage. Despite this difficulty, AE methods are commonly used in certain niche applications, such as the monitoring of pressure vessels. When a solid material is stressed, imperfections within the material emit short bursts of acoustic energy called "emissions." acoustic emissions can be detected by special receiver's acoustic emission wave propagation. Emission sources can be evaluated through the study of their intensity, rate, and location.

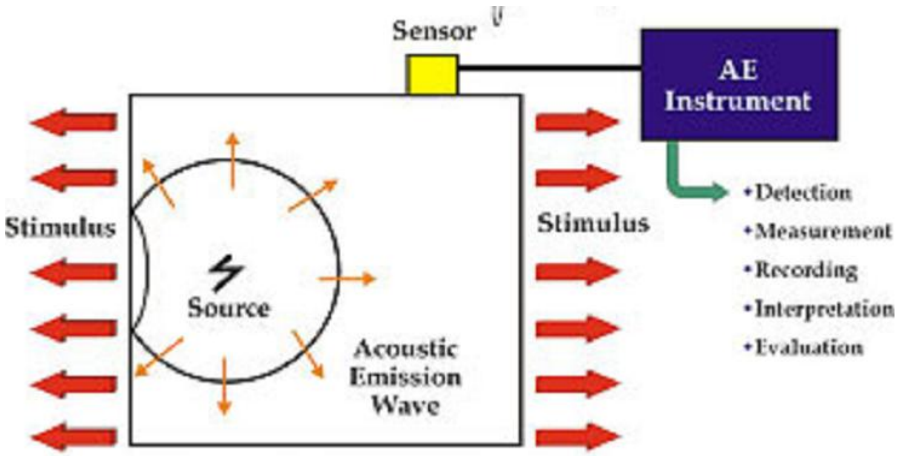


Figure 1.5: Acoustic Emission Testing Method [3]

1.5.8 Infrared/Thermal Testing: Infrared and thermal testing methods are characterized by the use of thermal measurements of a test object as it undergoes a response to a stimulus. Thermal imaging cameras are the most common sensing method. Passive imaging of machinery or electronics may be used to detect hot spots indicative of problems. Imaging of test objects after the application of energy can be used to monitor the flow of heat in the object, which is a function of material properties as well as boundaries. Flash thermography techniques have been very successful in imaging disbonds and delaminations in composite parts, for example. The high cost of quality thermal cameras was previously a drawback of the IR method, but recently these have become significantly less expensive.

1.5.9X-Ray Fluorescence Testing (XRF): X-ray fluorescence is one of the methods for NDT. The equipment contains radioactive sources or a low voltage x-ray generator, which sends out radiation. The exposed material then sends temporarily element specific radiation back, generating energy. As every element has its own atomic structure, this reflection will generate a different energy level for every element. This energy is measured and detected, thus identifying the alloy elements.

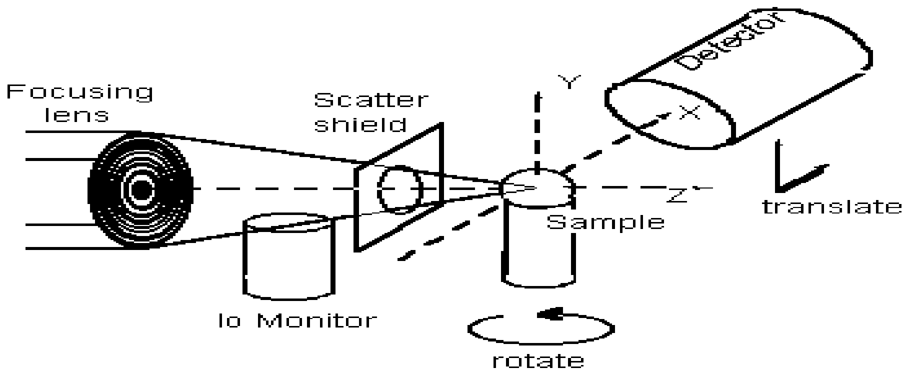


Figure 1.6: X-Ray Fluorescence Testing Method [3]

NDT technique has its own set of advantages and disadvantages and, therefore, some are better suited than others for a particular application. In NDT the method that will detect the defect or make the measurement with the highest sensitivity and reliability must be selected. The cost effectiveness of the technique must also be taken into consideration. **Table 1.1** provides some guidance in the selection of NDT techniques for common flaw detection and measurement applications.

Table.1.1 COMPARISON OF ULTRASONIC TESTING WITH OTHER METHODS [3]

Parameter	**Penetrant Testing**	**Magnetic Particle Testing**	**Ultrasonic Testing**	**Eddy Current Testing**	**Radiographic Testing**
Range of inspection	Large surface areas or large volumes of parts can be inspected rapidly.	Large surface areas of complex parts can be inspected rapidly.	Depth of penetration for flaw detection is superior to other methods.	Detects surface and near surface defects.	Can be used to inspect virtually all materials.
Geometry	Parts with	Can detect	Only single	Test probe	Detects

of part to be inspected	complex geometry are routinely inspected.	surface and subsurface flaws.	sided access is required.	does not need to contact the part.	surface and subsurface defects.
Type of surface needed	Requires a relatively smooth and nonporous surface.	Proper alignment of magnetic field and defect is critical.	Surface finish and roughness can interfere with inspection.	Ferromagnetic materials require special treatment for magnetic permeability.	Access to both sides of the structure is usually required.
Cost of inspection	low	Low	Low	Low	Moderate
Cost of equipment	low	moderate	Moderate	High	High
Surface preparation	Surface preparation is critical.	Surface preparation is less critical.	Minimum Part preparation is required.	Minimum Part preparation is required.	Minimum part preparation is required.

1.6 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:

- Pulse echo method
- Through transmission method
- Two transducer method
- Resonance method

All the above techniques are discussed below:-

1.6.1Pulse 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. The electrical signal is computer processed for display on a video monitor or TV screen as shown in figure 1.8. The display can show the relative thickness of the material, depth into the material where flaws are located (with proper scanning hardware and software) in the X-Y plane.

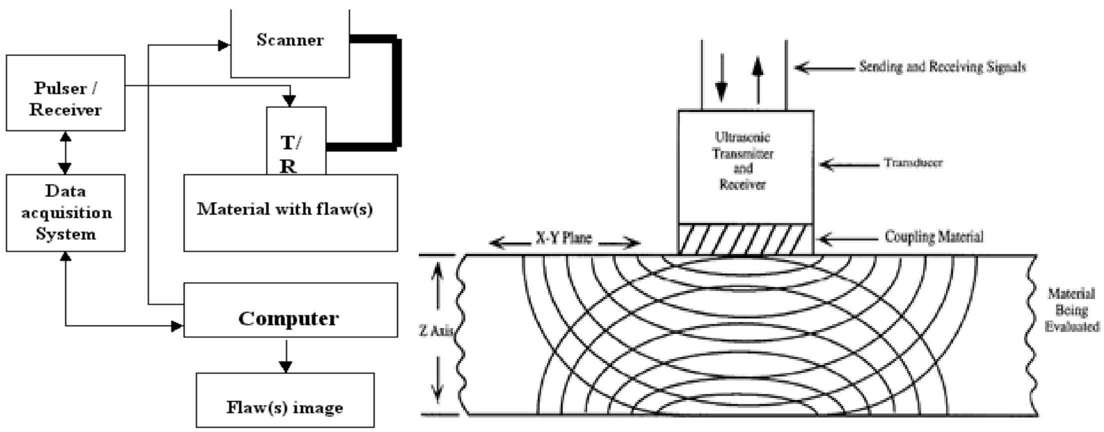


Figure 1.7: Arrangement of Pulse Echo Method [2]

1.6.2 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. One unit acts as transmitter and the other unit as receiver shown in figure 1.9. 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 result in the location of defects and flaws. In this method the presence of an internal defect is indicated by reduction in signal amplitude. Mainly in this method good mechanical coupling and alignment of the two probes is essential.

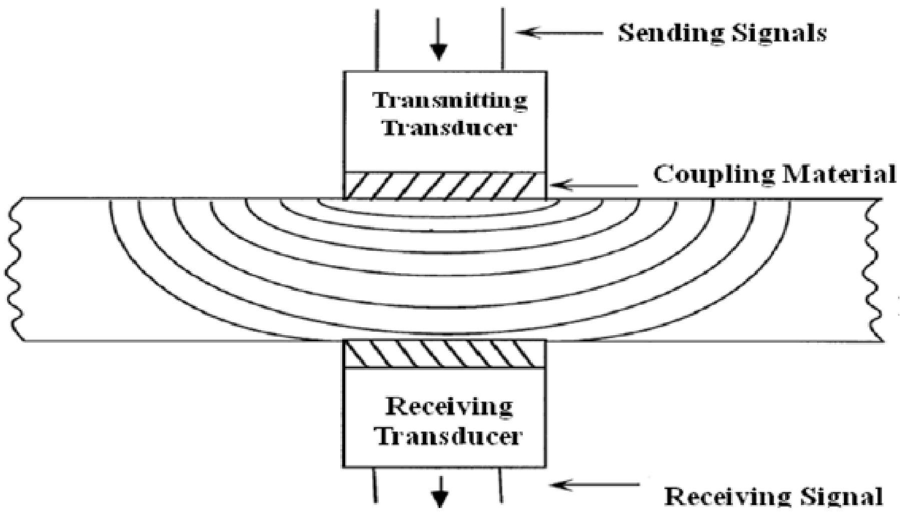


Figure 1.8: Through Transmission Method [2]

1.6.3 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 into the specimen by the transducer (T) and the echoes reflected from the back surface or any defect are received by the transducer (R) and displayed on the flaw detector screen. For specific applications like wall thickness measurement special type of transducers in which the transmitting and the receiving crystals are housed in a single unit are also used.

1.6.4 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 ultrasonic to find the magnitude of the defect in specimen.

1.7 ADVANTAGES AND DISADVANTAGES OF ULTRASONIC TESTING

Each NDT technique has its own set of advantages and disadvantages and, therefore, some are better suited than others for a particular application. The NDT technician or engineer must select the method that will detect the defect or make the measurement with the highest sensitivity and reliability. The primary advantages and disadvantages of ultrasonic testing when compared to other NDT methods are:

1.7.1 Advantages

Ultrasonic testing gives faster and accurate results. Also ultrasonic testing detects the defects more effectively. Some other advantages are as follows:

- It is sensitive to both surface and subsurface discontinuities.
- The depth of penetration for flaw detection or measurement is superior to other NDT methods.
- Only single-sided access is needed when the pulse-echo technique is used.
- It is highly accurate in determining reflector position and estimating size and shape.
- Minimal part preparation is required.
- It provides instantaneous results.
- Detailed images can be produced with automated systems.
- It is nonhazardous to operators or nearby personnel and does not affect the material being tested.
- It has other uses, such as thickness measurement, in addition to flaw detection.
- Its equipment can be highly portable or highly automated.

1.7.2 Disadvantages

For using ultrasonic testing machine skills are needed. Other limitation of ultrasonic testing is that very thin material not easily detected. Some other disadvantages are as under:

- Surface must be accessible to transmit ultrasound.
- Skill and training is more extensive than with some other methods.

- It normally requires a coupling medium to promote the transfer of sound energy into the test specimen.
- Materials that are rough, irregular in shape, very small, exceptionally thin or not homogeneous are difficult to inspect.
- Cast iron and other coarse grained materials are difficult to inspect due to low sound transmission and high signal noise.
- Linear defects oriented parallel to the sound beam may go undetected.
- Reference standards are required for both equipment calibration and the characterization of flaws.

1.8 CLOSURE

Structural Health Monitoring is important for long and safe life of various products used in different engineering fields. It is better if we use non destructive testing as one can find defects without damaging the material. All methods have their own advantages and disadvantages for specific application in terms of cost, geometry of part to be inspected, range of inspection, operating conditions etc. But in non destructive testing ultrasonic inspection method has certain advantages like low cost, accurate, nonhazardous, portable etc which make it more suitable over many others.

CHAPTER 2
GUIDED WAVES IN CYLINDRICAL GEOMETRY

GENERAL

Ultrasonic waves permit non-destructive testing of materials for the detection of component defects. Using this test procedure the precise location of cracks, pores, inclusions and fusion flaws can be determined. This method is used for testing metal, ceramic and plastic materials. 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. Ultrasonic wave propagation characteristics vary with change in the medium in which the wave propagates. A typical UT inspection system consists of several functional units, such as the pulse/receiver, transducer, and display devices. Images are generated either with a high-precision mechanical scanner or a phased array system. The magnitude of damage is found from the change in amplitude of the through transmission signal.

2.1 WAVE PROPAGATION THROUGH SOLIDS

The ultrasonic waves propagate in a number of ways in a medium. Wave propagation depends on material properties of the structure. 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

2.1.1 Longitudinal or Compressional waves

These waves are also called compression waves. In this type of ultrasonic wave alternate compression and rarefaction zones are produced by the vibration of the particle parallel to the direction of propagation of the wave. In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation. 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 comparison and expansion (rarefaction) movements.

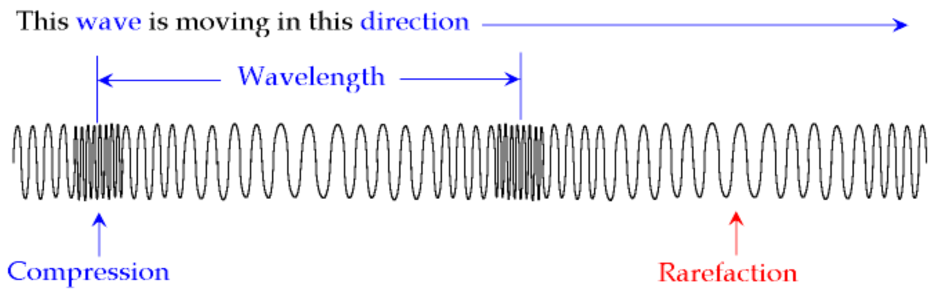


Figure 2.1: Propagation of Longitudinal waves [2]

2.1.2 Transverse or Shear wave

This type of ultrasonic wave is called a transverse or shear wave, as the particles oscillate at a right angle or transverse to the direction of propagation. Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. For such a wave to travel through a material, it is necessary that each particle of material is strongly bond to its neighbors so that, as one particle moves it pulls its neighbor with it, thus causing the ultrasound energy to propagate through the material. Shear waves are relatively weak when compared to longitudinal waves. Velocity is 50% less than that of the longitudinal waves. 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.

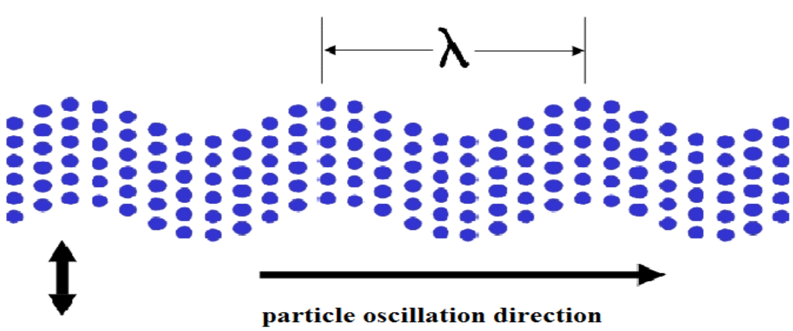


Figure 2.2: Propagation of Transverse waves [2]

2.1.3 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. These types of waves can only travel along a surface bounded on one side by the strong elastic force of the solid and on the other side by the nearly nonexistent elastic forces between gas molecules. Surface waves are essentially nonexistent in a solid immersed in liquid, unless the liquid covers the solid surface only as a very thin layer. In surface waves particle vibrations generally follow an elliptical path. The major axis is perpendicular to surface along which the waves are travelling. The minor axis is parallel to the direction of propagation. 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.

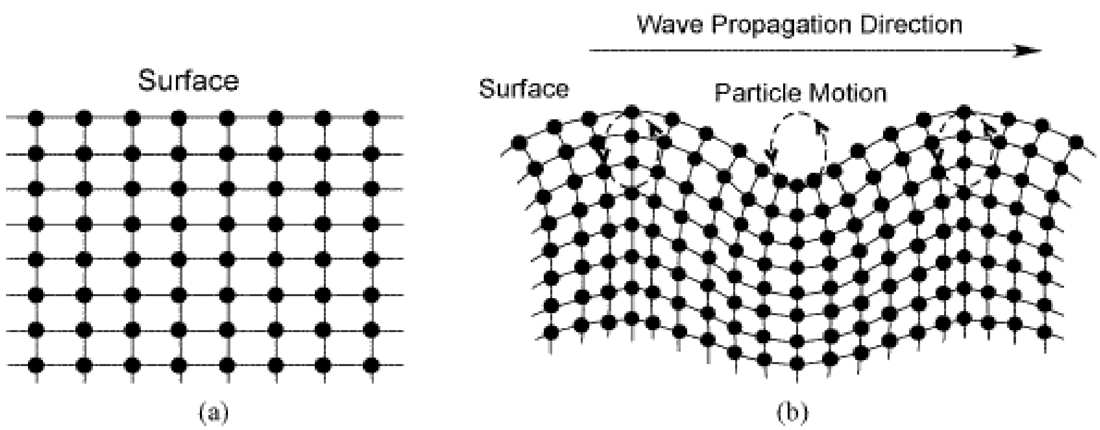
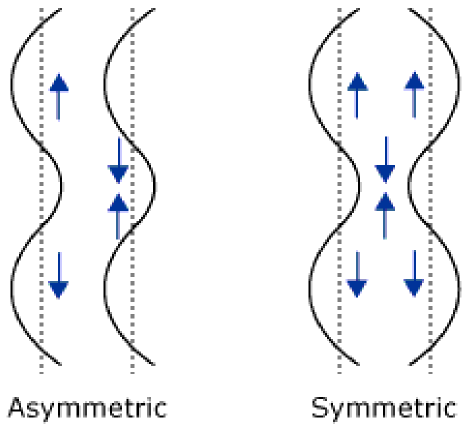


Figure 2.3: Propagation of surface waves [5]

2.1.4Lamb waves

Plate or Lamb waves can be propagated only in very thin plates or sheets. Lamb waves are the most commonly used plate waves in NDT. Lamb waves are complex vibration 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. 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.



(a) (b)

Fig.2.4 Lamb Wave mode (a) Asymmetric (b) symmetric [5]

2.1.5 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.

Thus these waves move according to their behavior. In actual movement of the particle decide which type of wave is. In longitudinal waves, the oscillations occur in the longitudinal direction, in the transverse the particles oscillate at a right angle to the direction of propagation. Propagation also depend on the type material like lamb waves can be propagated only in very thin metals, surface waves travel on the surface of a relatively thick solid material. The **table 2.1** below summarizes the wave modes possible in solids.

Table 2.1 Wave modes possible in solids [5]

Wave Types in Solids	**Particle Vibrations**
Longitudinal	Parallel to wave direction
Transverse (Shear)	Perpendicular to wave direction
Surface – Rayleigh	Elliptical orbit - symmetrical mode
Plate Wave – Lamb	Component perpendicular to surface (extensional wave)
Plate Wave – Love	Parallel to plane layer, perpendicular to wave direction
Stoneley (Leaky Rayleigh Waves)	Wave guided along interface
Sezawa	Antisymmetric mode

2.2. GUIDED WAVES

A wave having energy concentrated near a boundary, or between substantially parallel boundaries, separating materials of different properties is called as guided wave. In an unbounded elastic medium, bulk ultrasonic waves can propagate as homogeneous or inhomogeneous bulk longitudinal and shear waves. In a waveguide such as a pipe, rod, plate etc partial bulk waves reverberating between the boundaries of the waveguide are superposed to form a guided wave propagating along the structure. There are a large number of guided wave modes which can propagate in materials with different propagation characteristics. The propagation of guided wave modes in a pipe is affected by the media surrounding and inside the pipe. Three different families of modes are present in cylindrical waveguides: longitudinal, torsional and flexural modes. Each family of modes itself comprises an infinite number of modes. On the other hand, a large number of guided wave modes exist in pipes and plates. These are highly dispersive in nature as their velocity is a function of frequency. Guided wave testing on pipe is made possible by the controlled excitation of one (or more) of these wave forms that is then guided by the geometry of the pipe and travels along in the axial direction. These excited waveforms reflect from regions of change in the pipe stiffness or cross sectional area. Guided wave testing has proven to be an effective means of performing rapid condition assessments on extended lengths of piping, and shows great promise in monitoring applications.

2.2.1. Guided waves in cylindrical geometries

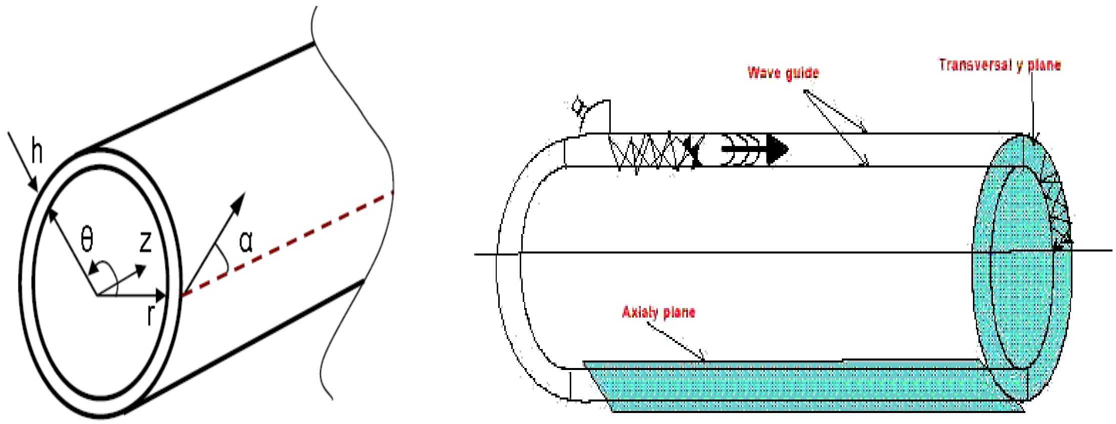


Figure 2.5: Hollow cylinders guided waves [3]

In hollow cylinders guided waves travel over large distances and propagate with multiple mode shapes. Therefore these waves can be used viably for integrity tests of large scale structures. With only a few sensor positions large areas of the structure under test can be monitored efficiently. The main drawback using guided waves in non-destructive testing (NDT), however, is the dispersive character of the wave propagation and the increasing number of propagating modes at higher frequencies. Due to this multi-modality and the diversity of the modes shapes, an echo signal generated by using guided waves is very complex and the analysis of this complex signal, thus, appears to be rather difficult. To overcome these shortcomings, different approaches were investigated in the past such as the limitation to low-frequency excitation. It involves using a single mode domain which exists in low frequency domain.

2.2.2. Nature of modes in cylinders

The dispersion curves for a system describes the solution to modal waves propagation equation and give the properties of guided waves like phase velocity, energy velocity, attenuation and mode shape). In general this information enables the prediction of the optimum test conditions and helps the understanding of the experiment result. The software disperse has been used to modal the cases.

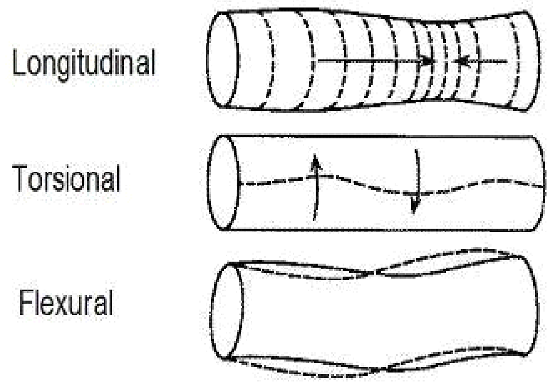


Figure 2.6: Different modes of cylindrical waveguides [1]

2.2.3. Attenuation of Waves

When sound travels through a medium, its intensity diminishes with distance. In idealized materials, sound pressure (signal amplitude) is reduced due to the spreading of the wave. In natural materials, however, the sound amplitude is further weakened due to the scattering and absorption. Scattering is the reflection of the sound in directions other than its original direction of propagation. Absorption is the conversion of the sound energy to other forms of energy. The combined effect of scattering and absorption is called attenuation. Attenuation is generally proportional to the square of sound frequency.

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

$$A=A_0e^{-\alpha Z}$$

Where;

A_0: initial (un-attenuated) amplitude

α: attenuation coefficient (Np/m)

Z: traveled distance (m)

2.3 REFRACTION AND SNELL'S LAW

When an ultrasonic wave passes through an interface between two materials at an oblique angle, and the materials have different indices of refraction, both reflected and refracted waves are produced. This also occurs with light, which is why objects seen across an interface appear to be shifted relative to where they really are. For example, if you look straight down at an object at the bottom of a glass of water, it looks closer than it really is. Refraction takes place at an interface of two materials due to the difference in acoustic velocities between the two materials. The **Figure 2.7** shows the case where plane sound waves traveling in one material enters a second material that has a higher acoustic velocity. When the wave encounters the interface between these two materials, the portion of the wave in the second material is moving faster than the portion of the wave that is still in the first material. As a result, this causes the wave to bend and change its direction this is referred to as refraction.

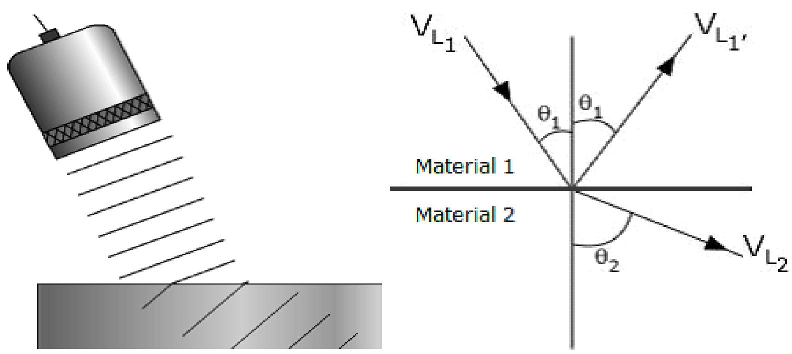


Figure 2.7: Shows a wave passes through interface [3]

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

$$\frac{\sin\theta_1}{VL_1} = \frac{\sin\theta_2}{VL_2} \qquad \text{...2.1}$$

Where,

V_{L1} and V_{L2}: the longitudinal wave velocities in the first and second materials.

θ_1 and θ_2: the angles of incident and refracted waves

In the diagram, there is a reflected longitudinal wave shown. This wave is reflected at the same angle as the incident wave because the two waves are traveling in the same material, and hence have the same velocities. This reflected wave is unimportant in our explanation of Snell's Law, but it should be remembered that some of the wave energy is reflected at the interface.

2.3.1 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 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. It should be noted that mode conversion occurs every time a wave encounters an interface at an angle. This mode conversion occurs for both the portion of the wave that passes through the interface and the portion that reflects off the interface.

Snell's Law holds true for shear waves as well as longitudinal waves and can be written as follows:

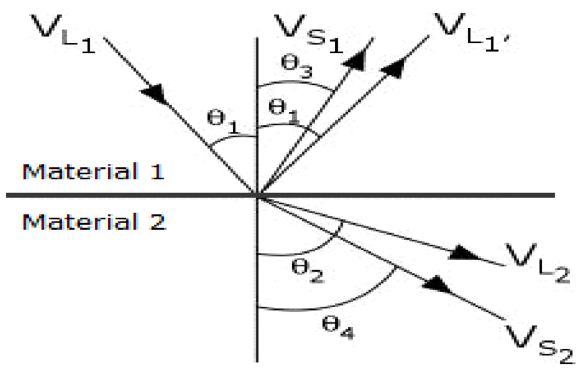


Figure 2.8: Snell’s Law [3]

$$\frac{\text{Sin}\,\theta 1}{VL1} = \frac{\text{Sin}\,\theta 2}{VL2} = \frac{\text{Sin}\,\theta 3}{VL3} = \frac{\text{Sin}\,\theta 4}{VL4} \quad \text{………………………………………………2.2}$$

Where:

V_{LI} AND V_{L2} : the longitudinal wave velocities in the first and second materials.

V_{S1} and V_{S2}: the shear wave velocities in the first and second materials.

θ_1 and θ_2: the angles of incident and refracted waves.

θ_3 and θ_4: the angles of converted reflected and refracted waves.

2.3.2 CRITICAL ANGLES

For small angles of incidence sound waves travelling at an angle from medium1 give rise to the longitudinal as well as shear waves, in the medium2 as shown in **Figure 2.9**. Such a situation is very confusing for NDT inspection, as both of these waves present in the medium2, 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 First Critical Angle

If the angle of incidence A is increased in the particular case when c2 > c1, angle B of the refraction longitudinal wave also increases till, for some specific value of angle A, the angle B becomes equal to 90^0 as shown in **Figure 2.9.** At this angle 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 (A1).

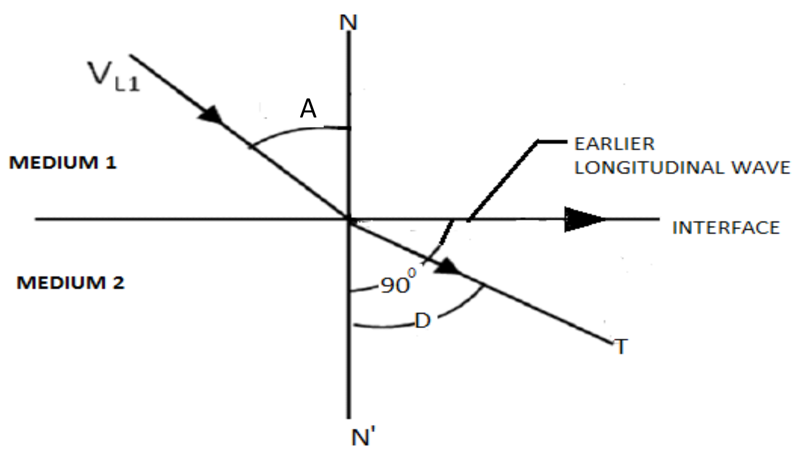


Figure 2.9: First Critical Angle [3]

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 90^0 the Snell's equation can be written as

$$\frac{\text{Sin A1}}{\text{C1}} = \frac{\text{Sin 90}}{\text{C2}}$$

Or

$A_1 = \text{Sin}^{-1}$ (c1/c2) ………………………………………………………2.3

Where, c1 and c2 are longitudinal velocities in the two media.

2.3.4 Second Critical Angle

If the angle of incidence A is further increased, a situation would arrive, when angle D of the refracted shear wave would be equal to 90^0. 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

$$\frac{\text{Sin } A_2}{\text{C1}} = \frac{\text{Sin 90}}{\text{C2}}$$

$A_2 = \text{Sin}^{-1}\left(\frac{C1}{C2}\right)$………………………………………………………2.4

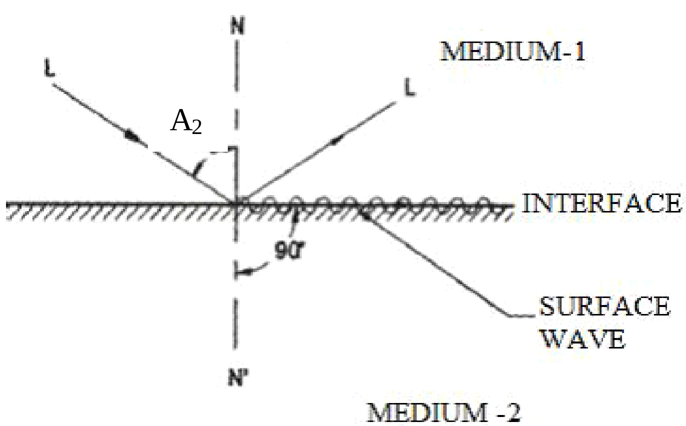


Figure 2.10: Second Critical Angle [3]

2.4. 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.

2.4.1 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 traveled distance within the material) is displayed along the horizontal axis shown below in **Figure 2.11**.

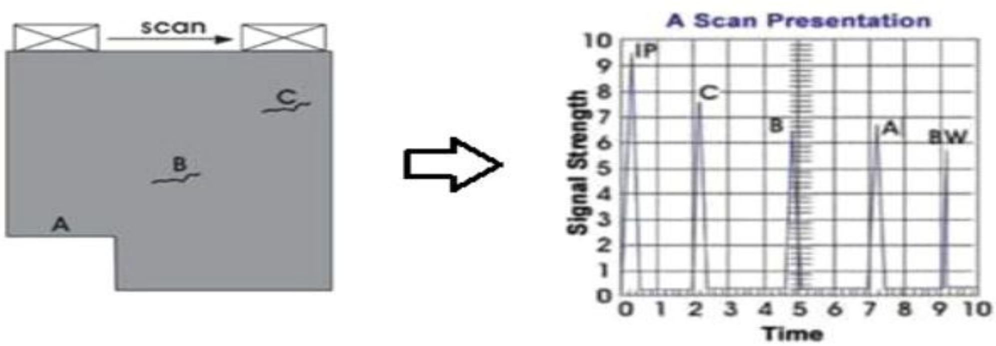


Figure 2.11: A-Scan Presentation [2]

2.4.2 B-Scan Presentation

The B-scan presentation is a type of presentation that is possible for automated linear scanning systems where it shows a profile (cross-sectional) view of the test specimen. In the B-scan, the time-of-flight (travel time) of the sound waves is displayed along the vertical axis and the linear position of the transducer is displayed along the horizontal axis. **Figure 2.12** represents B-scan

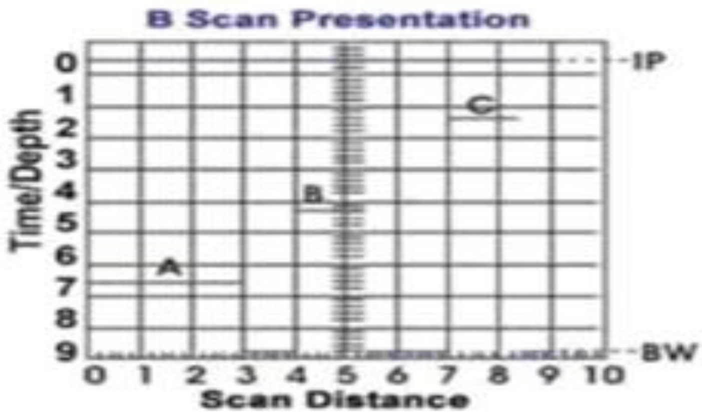


Figure 2.12: B-Scan Presentation [2]

2.4.3 C-Scan Presentation

The C-scan presentation is a type of presentation that is possible for automated two-dimensional scanning systems that 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 as shown in **Figure 2.13**. C-scan presentations are typically produced with an automated data acquisition system, such as a computer controlled immersion scanning system. 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.

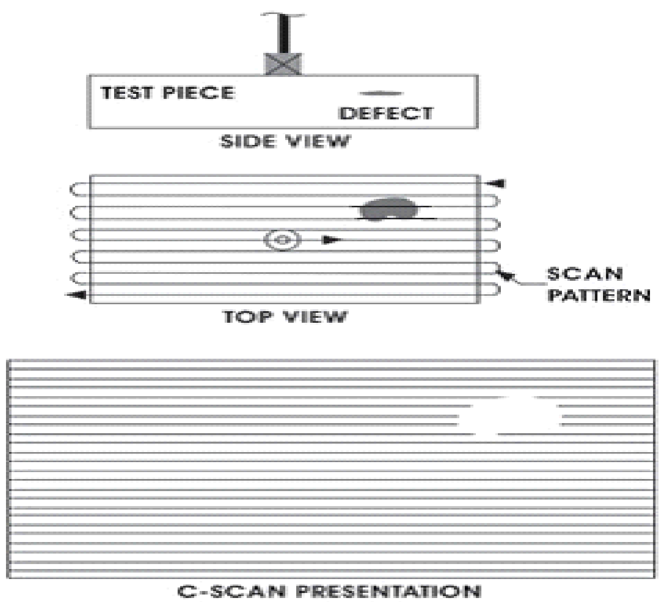


Figure 2.13: C-Scan Presentation [2]

2.5 PIEZOELECRIC TRANSDUCERS

A transducer is a device that converts one form of energy into another form. Ultrasonic transducers convert electrical energy into ultrasonic energy and vice versa by utilizing a phenomenon known as the piezoelectric effect. The materials which exhibit this property are known as piezoelectric materials.

Piezoelectric effect was first discovered by curie brothers. There is two types of effect. First, direct piezoelectric effect in which the piezoelectric material when subjected to mechanical pressure will develop an electrical potential across it. Second is inverse piezoelectric effect in which mechanical deformation and vibration produced in piezoelectric material whenever electric potential is applied to them. So, direct piezoelectric effect is used in detecting and inverse piezoelectric effect in the generation of ultrasonic waves.

2.5.1 CLASSIFICATION OF PIEZOELECTRIC TRANSDUCERS

Piezoelectric transducers are divided in three groups which are further divided in sub categories which are as under

1) Based on materials

- Piezoelectric crystalline transducers- These are the transducers of single crystal material in which the piezoelectric effect occurs naturally which are quartz, tourmaline, lithium sulphate, cadmium sulphide and zinc oxide.
- Polarized ceramic transducers- In this type of transducers piezoelectric effect has to be induced by polarization.

2) Based on angle of transmission

- Normal transducers- In this type of transducers the striking angle is normal to the plane surface and waves fall in axial direction of probe.
- Angle transducers- In this type of transducers the beam of sound reaches the bottom flat surface of the probe at an angle.

3) Based on application

- Contact type- In this transducer is in direct contact with the material or specimen to be tested.
- Non contact type- The transducers does not have any direct contact with the specimen but are placed at some distance. They are designed to operate in liquid environment.

2.6 CLOSURE

Ultrasonic Guided Waves are guided along particular geometry of the specimen. These waves interact with defects at suitable frequency can be recorded in form of signature on computer screen with the help of digitizer card. In this chapter how different modes of guided waves propagates in cylindrical geometries are discussed. Also a basic description about angles (Snell's law) and data presentation has been given.

CHAPTER 3

LITRATURE REVIEW

3.1 GENERAL

Ultrasonic is a very efficient way of detecting defects in NDT. So these can be very efficiently used to detect defects in cylindrical geometry. Ultrasonic guided waves can be produced in a structure by a variety of different techniques including angle beam transducers, comb type transducers, EMATs and magnetostrictive type sensors. Every natural wave guided has associated with a set of dispersion curves that presents to us the wave propagation possibilities in that structure. At each point of a dispersion curve there is a different wave structure. This chapter presents a review of literature on utilization of ultrasonic guided waves for damage detection in pipes, corrosion monitoring and cylindrical geometry.

Predoi *et al*. [6] used guided waves for the inspection of hollow cylinders. The steel tubes used in experiments were of 14 mm outer diameter and 12 mm inner diameter and 100mm long. Six tubes were tested, one having no notch (standard tube), four having a 0.6 mm wide notch in the center of tubes, with depths of 0.3,0.5, 0.7, 0.8 mm. The numerical and experimental results show that the sensitivity of modes to defects dependent on the selected mode, frequency and the geometry of the notch.

Lowe *et al*. [7] studied the detection of corrosion in insulated pipes. Methods involving point-by-point inspection were expensive because of the need to remove the insulation. An alternative method was given by researchers in which guided waves propagate in the walls of the pipes, and reflections from defects were detected. Pipes in the range of 2-12 inch were being considered. The testing employs pulse-echo arrangements from single location. The insulation was removed at just one location on a pipe and the signals was then transmitted and received using a ring transducer made up of dry coupled piezo-electric elements. The mode which was chosen for excitation in the inspection system is the axially symmetric L (0, 2) and F (1, 3) mode at about 70 kHz. Defects like notch and crack were easily detected by these modes.

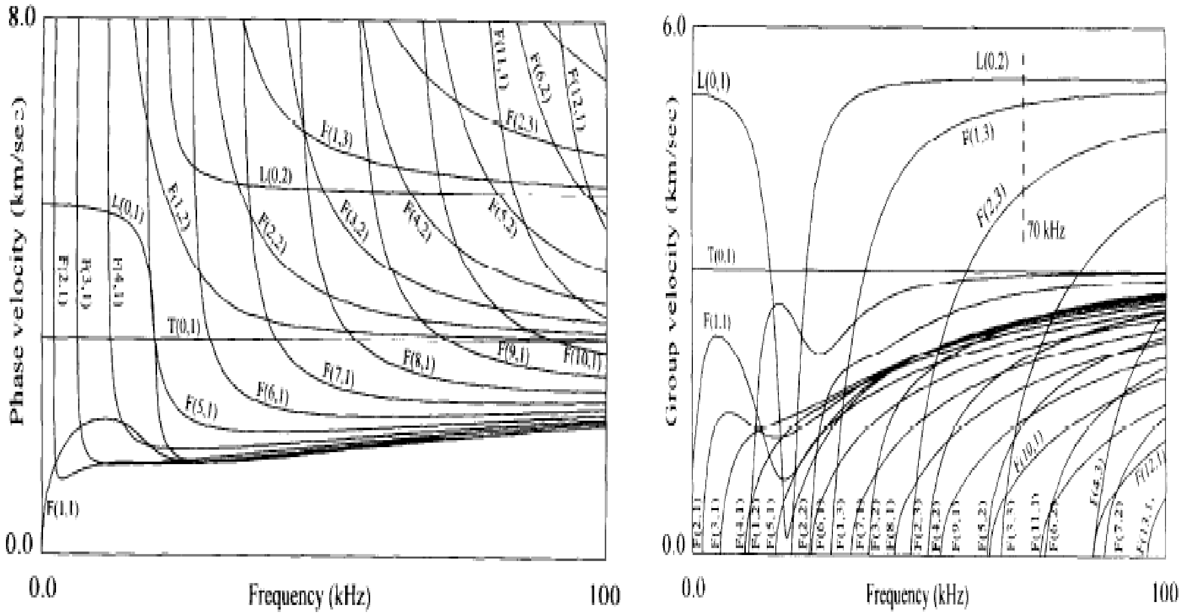


Figure 3.1: Phase and group velocity dispersion curves for 76 mm (nominal 3 in.) diameter pipe [7]

Aristegui *et al*. [8] investigated wave propagation characteristics with fluid loading on both inside and outside of the pipe. Experiment had been performed on a copper pipe having inner radius 6.8mm, wall thickness 0.7mm and 2m long. At the frequency of 250 kHz longitudinal transducer was attached. Mainly L (0, 1) and L (0, 2) modes were studied. Work proposed that in strongly leaky system the group velocity calculations was not valid and energy velocity must be used.

Na *et al*. [9] studied that pipes filled with concrete were usually exposed in water, thus the outside corrosion of the steel pipe can reduce the wall thickness and due to the corrosion-induced delarnination of internal concrete can increase internal pressure. To avoid this, inspection by guided waves had been suggested. A special coupling mechanism for transmitting the guided waves is introduced for the experimental study. Mortar-filled steel pipes containing four different degrees of separation were inspected. The pipe length taken is 916mm and the outer and inner diameters of the pipes are 22.36 mm and 19.26 mm, respectively. As the corrosion increases defect increases and rise in amplitude had been shown in **Figure 3.2.**The study shows the feasibility of using guided waves for underwater inspection of concrete-filled steel pipes.

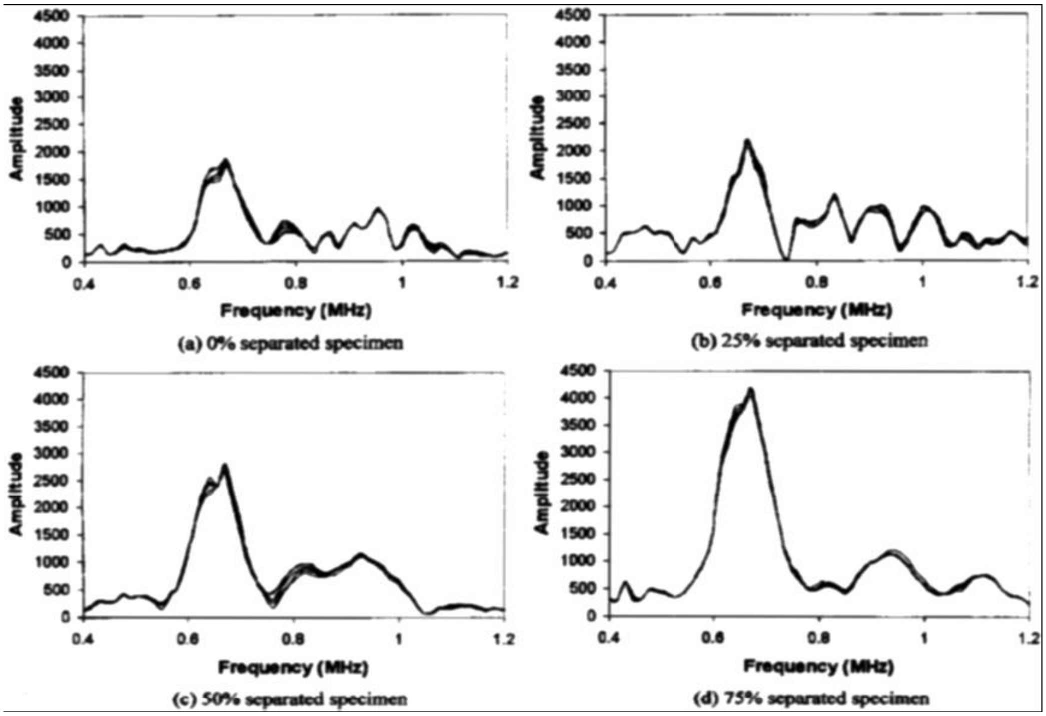


Figure 3.2: Rise in amplitude as the separation % increase between concrete and pipe. [9]

Na and Kundu [10] used ultrasonic cylindrical guided waves for underwater pipeline inspections. Three different types of mechanical defects gouge, removed metal, and dent were fabricated in small diameter, 22.22-mm aluminum pipes. Experimental set up is shown in **Figure 3.3.** To efficiently propagate the antisymmetric (flexural) cylindrical guided waves through the aluminum pipe in water, a new transducer holder device was designed. Transducers were excited using a MATEC 310 gated amplifier by tone burst signals from a WAVETEK 395 function generator. Here, the central frequency of the transducers was 500 kHz. The distance between the transmitter and receiver was 500 mm. The strongest signals were obtained for transducer incident angles between 20° and 51°. Time histories were converted to V(f) curves, or received signal amplitude versus frequency curves. From the amplitude of these V(f) curves, the type and extent of the mechanical can be estimated. This investigation shows that the new coupler device can be effectively used for health monitoring of underwater pipelines using guided waves

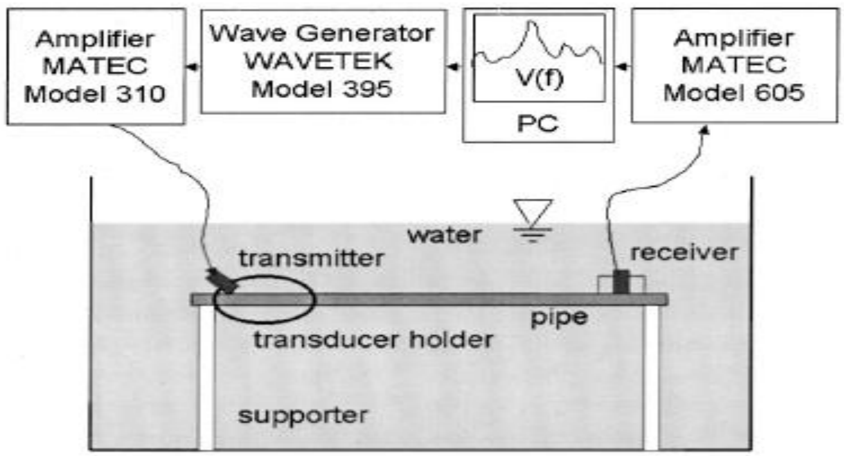


Figure 3.3: Schematic of experimental setup [10]

Demma *et al.* [11] presented the use of ultrasonic guided waves for the rapid screening of pipelines in service. Implementation of the method enables the localization of the defects along the length of the pipe and offers a rough estimate of defect size. Steel pipe 77.9 mm inside diameter, 5.5 mm thickness were used at 35 kHz frequency. The technique used the longitudinal L (0, 2) and T (0, 1) mode. A systematic analysis of the effect of pipe size, defect size, guided wave mode and frequency on the reflection from notches was studied. The maximum and minimum value of the reflection coefficient at varying axial extent are identified and used for the purpose of defect sizing. Maps of reflection coefficient as a function of the circumferential extent and depth of the defect were presented. Correction factor for different pipe sizes, location of defect in the cross section, ultrasonic guided wave mode and excitation frequency had been presented.

Siqueira *et al.* [12] studied the applications of guided waves for pipe inspection, since its one-dimensional geometry allows inspecting long distances in a short time. A carbon steel pipe measuring 1850 mm in length, 152 mm in diameter and 8 mm in thickness was tested with a 500 kHz transducer. The signals were acquired using the pulse–echo setting. In order to improve the evaluation of results, frequency bandpass filters and wavelet analysis were tested. The analysis of results obtained in tests performed in a low-carbon steel pipe using ultrasonic guided waves and signal processing via bandpass filters and wavelet transform showed that the ultrasonic guided waves were capable of traveling long distances without substantial attenuation, and were able to reach the reception point with a reasonable signal ratio, even when a single transducer was utilized. **Figure 3.4** shows that defect was detected and when the defect thickness increases rise in amplitude had been found.

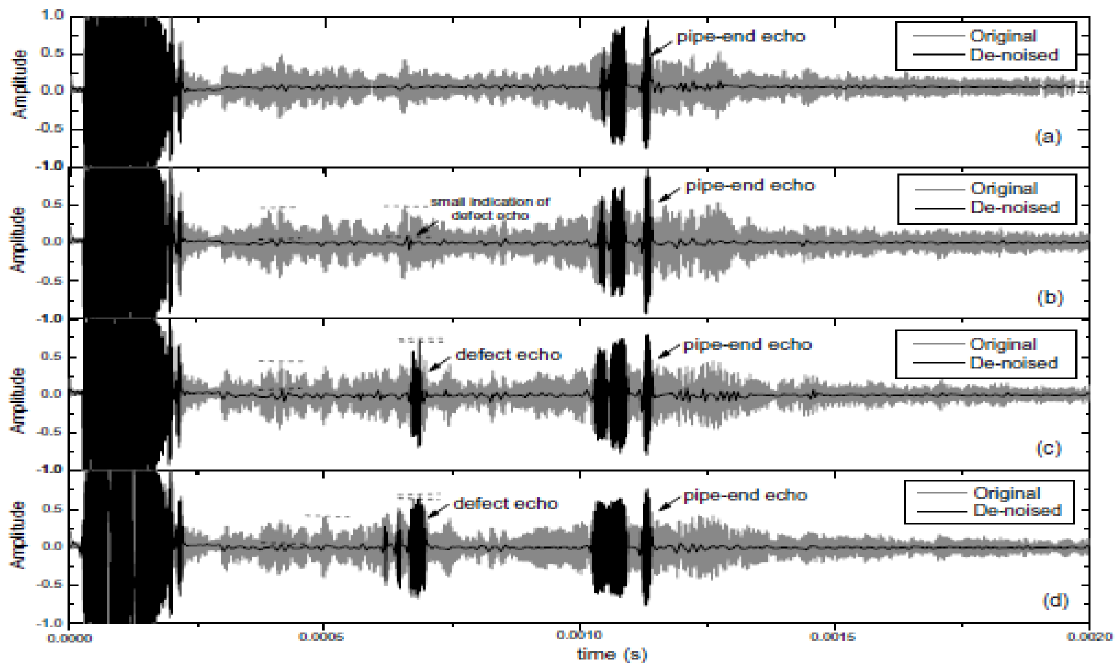


Figure 3.4: Original and denoised signals. (a) no defect; (b) defect mm; (c) defect 7 mm and (d) through defect. Dashed lines indicate the peaks used to calculate the S/N ratios. Transducer: 500 kHz. Incidence angle: 70. [12]

Li [13] used ultrasonic guided waves for long-range pipe inspections. The technique was based on detecting the guided wave echoes reflected from pipe defects located at a remote distance. The axial location of the defect from the transducer was determined by the arrival time of the echo. Specimen used was 76 mm long 3 in. in diameter with a wall thickness of 5 mm. An eight element circumferential array is placed around the pipe end, as shown in **Figure3.5**. Each element is an angle beam transducer that generates L (0, 1) mode at a frequency of 470 kHz. A circumferential guided wave array was built for sending and receiving guided waves along the pipe. All of the elements were connected to a single channel pulser/receiver through multiplexers. An algorithm based on two-dimensional (2D) blind deconvolution is developed to process the guided wave echoes acquired by the multiplexed circumferential transducer array.

The output of the algorithm can be utilized for evaluating the circumferential distributions and geometry of the defects. Although the experimental demonstration was realized by an eight-element array, more elements are needed for practical inspection work to achieve a better resolution for the circumferential mapping.

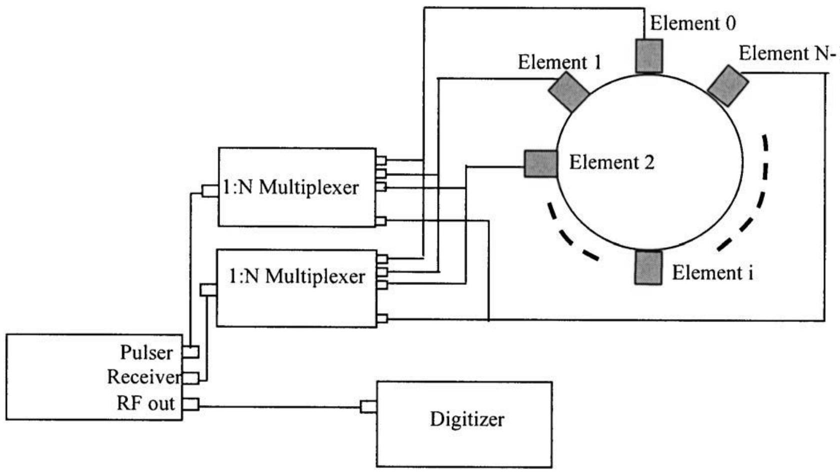


Figure 3.5: Sketch of the multiplexed circumferential array system [13]

Luo *et al.* [14] used guided wave phased-array focusing techniques in the long range guided wave inspection of industrial pipelines. Advantages of this were longer inspection distance, greater wave penetration power and higher detection sensitivity. For reasons of protection, safety and thermal efficiency, a large percentage of pipes were coated and buried underground. A phased-array focusing study for guided waves was now considered on pipelines with viscoelastic coatings. Longitudinal guided wave focusing axisymmetric wave propagation was studied in a bare pipe and a pipe with a viscoelastic coating. First, an investigation on whether the coating has an effect on the axisymmetric guided wave propagation was reported. Based on the result of a single channel, phased array focusing with 8-channel segments was studied. This study provides a very useful tool and guidance for the analysis and examination of guided wave focusing in a real field pipeline under various coating and environmental conditions. Modeling studies show that phased array focusing with longitudinal waves increases the signal energy by 16 dB for a certain propagation distance, indicating a much longer propagation distance and also improved defect detection sensitivity.

Shivaraj *et al.* [15] used higher order cylindrically guided ultrasonic waves for the detection and sizing of hidden pitting-type corrosion in the hidden crevice regions (between the pipe and the pipe supports) without lifting or disturbing the structural layout arrangement of the pipelines. The guided waves were generated using a piezoelectric crystal based transducer, located at the top region of the pipes, in a pulse-echo mode. Pipe sample of 168 mm diameter and 10.5 mm wall thickness was used. The system was validated on pipes ranging from 6 in. to 24 in. outer diameters of wall thicknesses up to 12 mm, by mapping defects as small as 1.5 mm diameter and 25% penetration wall thickness. A 2D finite element model using ABAQUS was used to understand the wave propagation in pipe wall. It was suggested that guided wave at a relatively high frequency of 1 MHz can be used for pipes with wall thicknesses of the order of 10 mm or less for the detection of pitting-type corrosion defects using circumferential guided wave modes.

Jing and Rose [16] studied guided wave flexural modes in cylinders can be generated by a partial source loading or any nonaxisymmetric discontinuity. They are especially important for guided wave mode control and defect analysis. The problem of guided wave propagation in free hollow cylinders with viscoelastic coatings was solved by a Semi-Analytical Finite Element (SAFE) method. Guided wave dispersion curves and attenuation characteristics for both axisymmetric and flexural modes were presented. Due to the fact that dispersion curve modes obtained from SAFE calculations were difficult to differentiate from each other, a mode sorting method is established to distinguish modes by their orthogonality. Theoretical proof of the orthogonality between guided wave modes in a viscoelastic coated hollow cylinder was provided. Wave structures were also calculated and discussed in view of wave mechanics in multilayered cylindrical structures containing viscoelastic materials.

Rose *et al.* [17] suggested that focusing of guided wave beams is a key for success, compared to conventional axisymmetric excitation. Guided wave scanning using both longitudinal and torsional modes was essential to improve sensitivity and reliability. In this paper benefits of using both torsional and longitudinal guided wave modes for inspection were discussed. Experimental results are presented that showed that neither torsional nor longitudinal modes, by themselves, can find all defects. **Figure 3.6** show that circumferential displacement profiles, obtained using phased array focusing, can be used to identify and inspect welds and to locate the circumferential position of the defects.

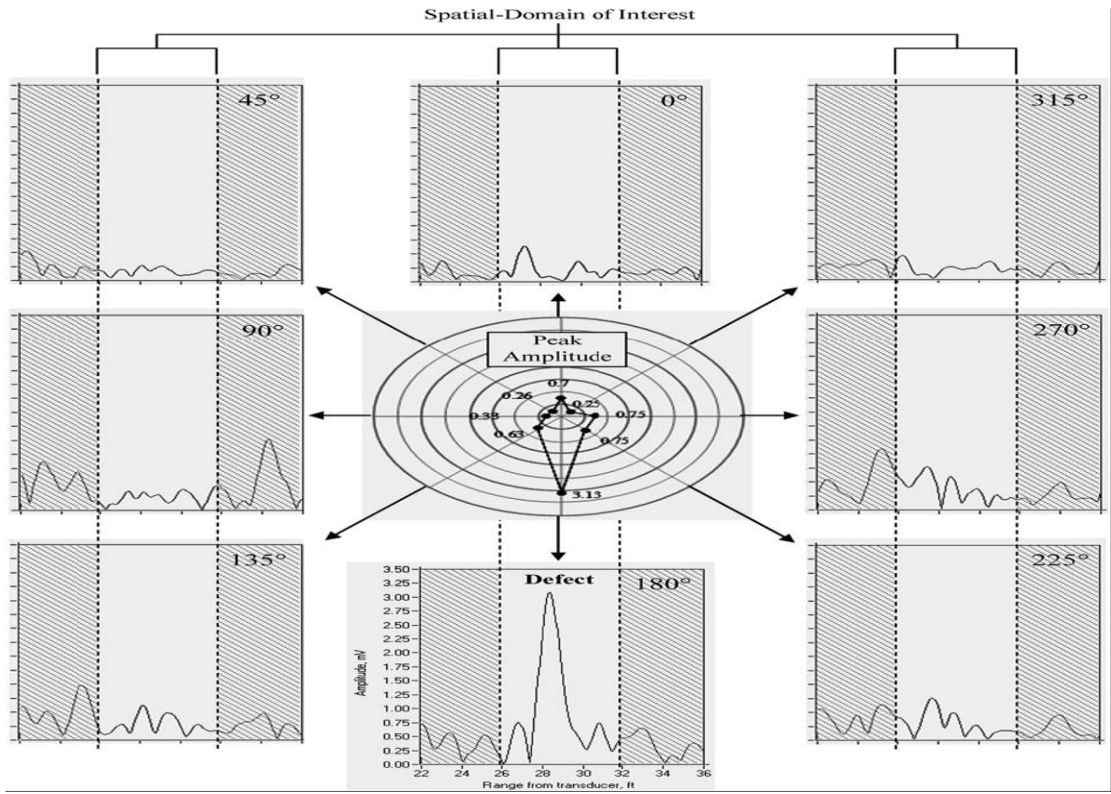


Figure 3.6: Phased array focusing technique at 8 different angles was taken on 16inch diameter coated pipe. Sharp peak indicates that there is a defect located in the bottom octant 180°. [17]

Satyarnarayan *et al.* [18] generated guided waves in mild steel (MS) pipe specimens containing artificially created axial notches (simulating axial cracks) and pinholes (simulating pinhole-like defects) of different sizes and corrosion under pipe supports. The characteristics of these guided waves had also been studied with 2.25MHz linear phased array transducer and 1MHz conventional circular transducer. These higher frequency modes were explored for their ability to detect and size defects. The signals obtained for all transducer configurations compared for their ability to locate, detect and size the above-mentioned defects. The amplitudes of the experimentally obtained signals were successfully used to size the defects. Notches of varying depths i.e., 20%, 40%, 60% and 80% of the thickness were made as shown in **Figure 3.7** and by drop in amplitude damage detection had been noted.

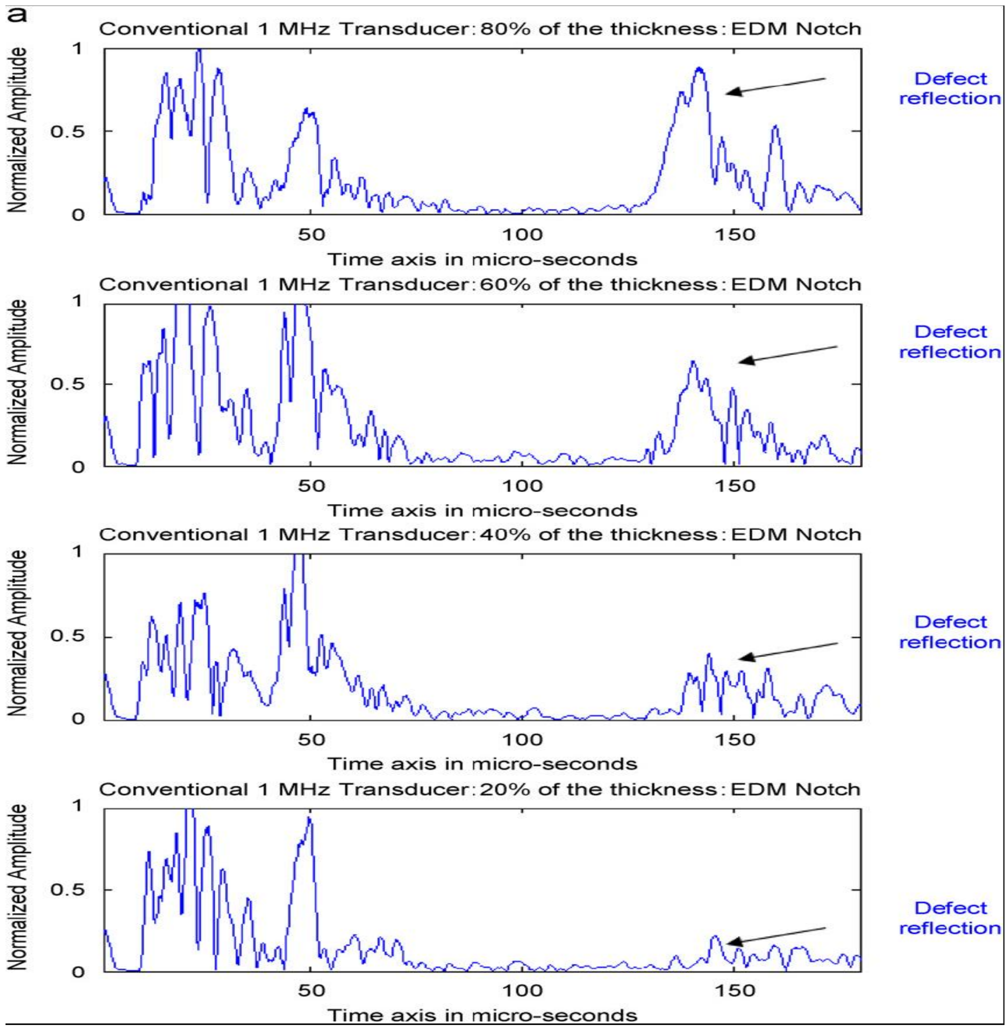


Figure 3.7: Shows drop in amplitude voltage as % of notch depth increases. [18]

Miki *et al*. [19] studied guided wave inspection technique was effective as detecting defects like corrosion in piping. Effectiveness to the straight parts in piping by the guided wave inspection had been clarified by many researches. The inspection performance using guided wave decreases due to the unwanted wave when there is a bend part in the inspection area. Phased array method was used to overcome this problem. Steel pipe with a diameter of 61mm, wall thickness of 3.7mm, and length of 5.5m were used. The adopted frequencies in this experiment were 40 kHz and 120 kHz. The delayed pulse by phased-array methods was set from the reflected wave which was transmitted from a local defect, and it was calculated based on time reversal theory. This transmission wave was confirmed by one experiment using the guided wave focused over the bend zone. Thus, the unwanted wave caused in the bend zone could be suppressed. In addition, the reception signal processing that considered the high-order modes was examined in the second experiment on reflected wave evaluation. By combining this transmission control with the reception signal processing, it was judged that the detection performance for local defects over the bend zone could be improved.

Zhu *et al*. [20] presented the method to detect cracks in large trusses that combines the advantages of UGWs with the extraction of defect-sensitive features to perform a multivariate diagnosis of damage. The probing hardware consisted of a data acquisition system that controlled the generation and detection of ultrasonic signals by means of piezoelectric transducers made of lead zirconatetitanate. Study was mainly focused on the detection of the onset and propagation of cracks induced on the fillet of the joint of a real truss structure. An array of 11 PZTs was used. The time waveforms were processed to generate a set of relevant damage sensitive features used to construct a uni or multidimensional damage index.

Wang *et al*. [21] observed that reflection signal from a defect in the process of guided wave-based pipeline inspection usually includes sufficient information to detect and define the defect Experiments had been conducted on a steel pipe with external diameter of 34 mm, a wall thickness of 4 mm and a length of 2030 mm. Frequencies ranging from 0.1MHz to 0.24 MHz were chosen for the pipe under examination because the L (0, 2) mode excited accordingly is non-dispersive in this frequency range. These curves were calculated using the DISPERSE program. Piezoelectric transducer was bonded to one end of the pipe to generate and receive guided waves. Defects like axial length defects and corrosion were detected in pipelines. The experimental results of artificial defects and real corrosion in sample pipes were considered to demonstrate the effectiveness of the proposed method. The investigation was limited to circumferential defects in straight, empty pipelines.

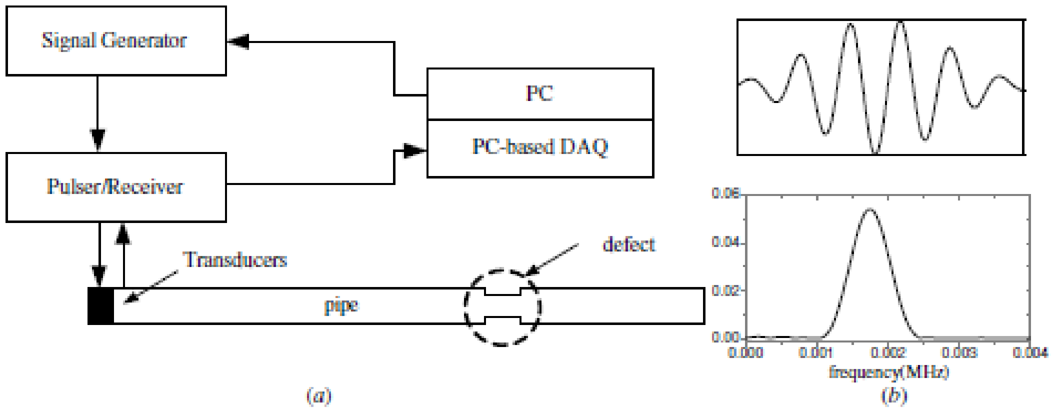


Figure 3.8 :(*a*) Schematic representation of the experimental setup; and (*b*) the excited tone burst signal and its FFT spectrum [21]

Shelke *et al*. [22] studied that guided waves were sensitive to structural damages encountered on their path of propagation and for this reason this technique was very efficient for distinguishing defective structural components from defect-free ones. A defect-free 1200 mm long seamless steel pipe was taken. The outer and inner diameters of the pipe are 21.4 mm and 16.4 mm, respectively. Then, a hole of 1 mm diameter was drilled in the pipe wall at a distance of 450 mm. Noncontact type transducers were used to detect a small defect on the pipe wall and estimate its location and size from a long distance when the reflected signal from the defect cannot be clearly identified. Electro-magnetic acoustic transducers (EMATs) were used here to generate guided waves in the pipe by the noncontact technique. Work shows how small a defect in a pipe wall can be detected and its location and dimension can be estimated using relatively low frequency guided waves generated and received by EMATs even when the defect signal was not clearly visible in the time history plot. Dispersion curves were used to determine the group velocities of different guided wave modes.

Korde *et al*. [23] investigated that elastic properties of materials can be easily determined from the ultrasonic wave velocity measurement. It was purposed that attenuation of ultrasonic guided waves can be correlated with the material ageing or duration of heat treatment and material hardness. To this aim six identical aluminum 2024 alloy plate specimens were subjected to different durations of heat treatment at 150 ºC and were inspected nondestructively propagating Lamb waves through the specimens. Attenuation of the Lamb wave was found to be inversely related to the hardness. Rockwell hardness test was performed to corroborate the ultrasonic observations. In comparison to the Rockwell hardness test the ultrasonic inspection was found to be more sensitive to the heat treatment duration and material ageing. From these results it is concluded that guided wave inspection method is a reliable and probably more desirable alternative for characterizing the hardness and microstructure of heat treated materials.

Liu *et al*. [24] studied guided waves are a very attractive methodology to inspect multi-hole steel floral pipes as they offer long range inspection capability, mode and frequency tuning, and cost effectiveness. 4.2 m long steel pipe with external diameter 89 mm and wall thickness 5 mm were used. Piezo-electric transducers array at low frequency longitudinal guided wave modes L(0,2) taken. The relation between the number of grouting holes and the peak-to-peak amplitude of the first end-reflected signal was obtained. The effect of the grouting holes in steel floral pipes on the propagation velocity of the L (0, 2) mode at 30 kHz was analyzed. Low frequency longitudinal guided wave modes have potential for the non-destructive long range inspection of multi-hole steel floral pipes. Furthermore, the propagation velocity of the investigated L (0, 2) mode at 30 kHz decreases linearly with the increase of the number of grouting holes in a steel floral pipe.

3.2 CLOSURE

In this chapter review of previous work has been carried out. Using guided waves for damage detection in cylindrical geometries has been studied. Various researchers have used ultrasonic guided waves to detect and locate defects in pipes subjected to varied boundary conditions for dents, gauges, notch etc. Various modes at different frequencies are sensitive to different types of defects. Most of the reported work includes the use of contact type transducers arrangements for generating suitable mode in the pipe geometry. Also a corrosion defect in most of the work has been reported as simulated material loss defect. So it is proposed to conduct non contact investigations in the present study to detect the presence and extent of actual corrosion losses.

CHAPTER 4

SELECTION OF OPTIMUM FREQUENCY AND MODE

4.1 GENERAL

This chapter discusses the size & specifications of various specimens and the experimental setup required to carry-out the proposed work. Study has been done to find the suitable frequency and mode of the guided waves. Guided waves are generated offering the piezoelectric transducer at a particular angle with respect to the submerged specimen. Experiments are performed under submerged condition by using immersion type of Transmitter/Receiver probes. The focus of study is to investigate the suitable frequency and mode in hollow cylindrical geometries filled with water inside.

4.2 EXPERIMENTAL SET UP

4.2.1 Specimen detail

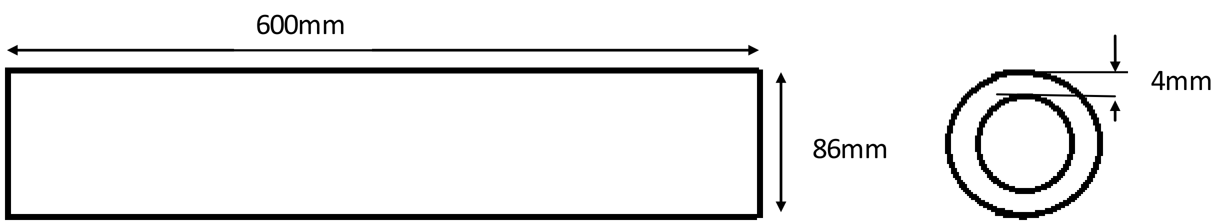


Figure 4.1: Detail of mild steel pipe

Mild steel pipe is used for performing the experiment. The pipe taken is 600mm in length, 86mm external diameter and 4mm thick as shown in **Figure 4.1.**

The experimental setup consists of pulser/receiver system that generates the electric pulses for every given time interval. These pulses are sent to the transducer which converts the pulse to ultrasonic wave. Transmitter transducer transmits the ultrasonic pulse to the specimen through a coupling medium (water) and on the other side receiving transducer receives the pulses. Received pulses again sent to pulser/receiver system from which it is then digitized using digitizer card. The digitizer card is attached to the computer which displays pulses in the form of voltage- time signature on the screen as shown in **Figure 4.2**. Experiment is performed under immersed condition. Pipe has been used for testing and technique employed is through transmission method.

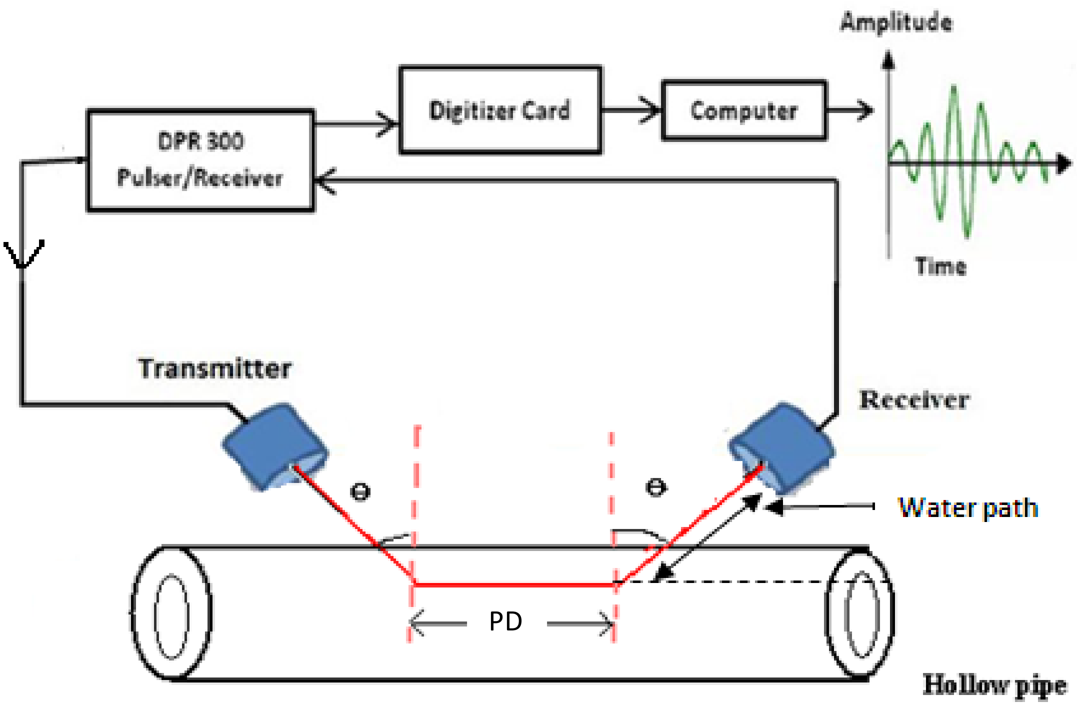


Figure 4.2: Schematic arrangements for ultrasonic testing

Experiment set up consists of following components:

1. Transducers
2. Pulser/receiver system
3. Digitizer card(in computer)
4. Scanning setup
5. Water tank

Figure 4.3: Ultrasonic experiment set up

4.2.2 Transducer

It is a single element longitudinal wave transducer. It can be used in straight beam flaw detection, thickness gauging, detection of crack, hole, material characterization and sound velocity measurements. OLYMPUS PANAMETRICS Standard transducer of 0.5 MHz (1”diameter) and 1 MHz (1” diameter) has been used as shown in **Figure 4.4**

(a) **(b)**

Figure 4.4: Immersion probes (a) 0.5 MHz (b) 1 MHz

4.2.3 JSR Ultrasonic’s DPR 300 Pulser/ Receiver System

DPR300 pulser produces a high voltage electrical excitation pulse and applies this pulse to the instrument’s Transmitter/Receiver connector. An ultrasonic transducer connected to the T/R connector via a length of 50Ω 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 DPR300configured 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 DPR300receiver 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: 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.

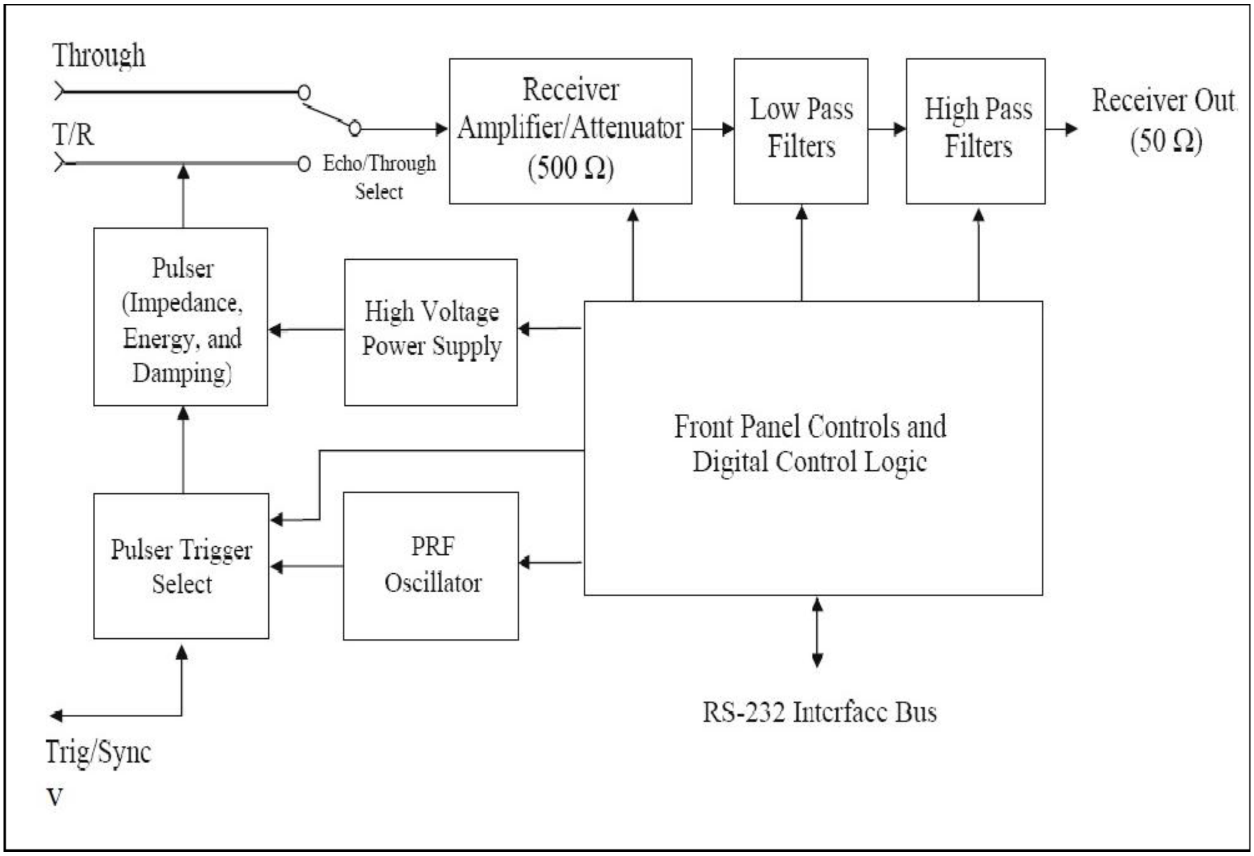


Figure 4.6: Circuit diagram of pulser/receiver system

Receiver amplifier: It controls the amplification or attenuation of signals processed by theDPR300 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 theDPR300 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 µJoules minimum, 304 µjoules 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 for475V pulsers.
Sync Output	Maximum +5 V, tr< 30 ns, tw = 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	0° (non-inverting)
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 µVpk-pk input referred(measured at 60dB,35 MHz bandwidth)
Output Impedance	5
Output Voltage	± 0.5 V into 50
Bandwidth	.001-35 MHz (-3 dB) or .001-50 MHz

4.2.4 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± 1% @ DC
Connector	BNC, gold-plated
Channels	Two
Coupling	DC
Maximum Input Voltage	±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

4.2.5 Scanning set up

This set up has four degree of freedom, three translations for positioning of transducer over specimen and one rotational to arrange the transducers at a specific angle so as to get a desirable mode. The transducers are mounted in a holder and naturally coupled with water by putting pipe transducer setup in water. The excitation signal consists of a negative spike pulse with its duration ranging from 10-70 ns. The least count for rotational motion is 0.1 degree. The maximum movement in X-direction is 120 cm, Y-direction is 70 cm, Z direction is 10 cm, and rotation allowed is 0-30 degree.

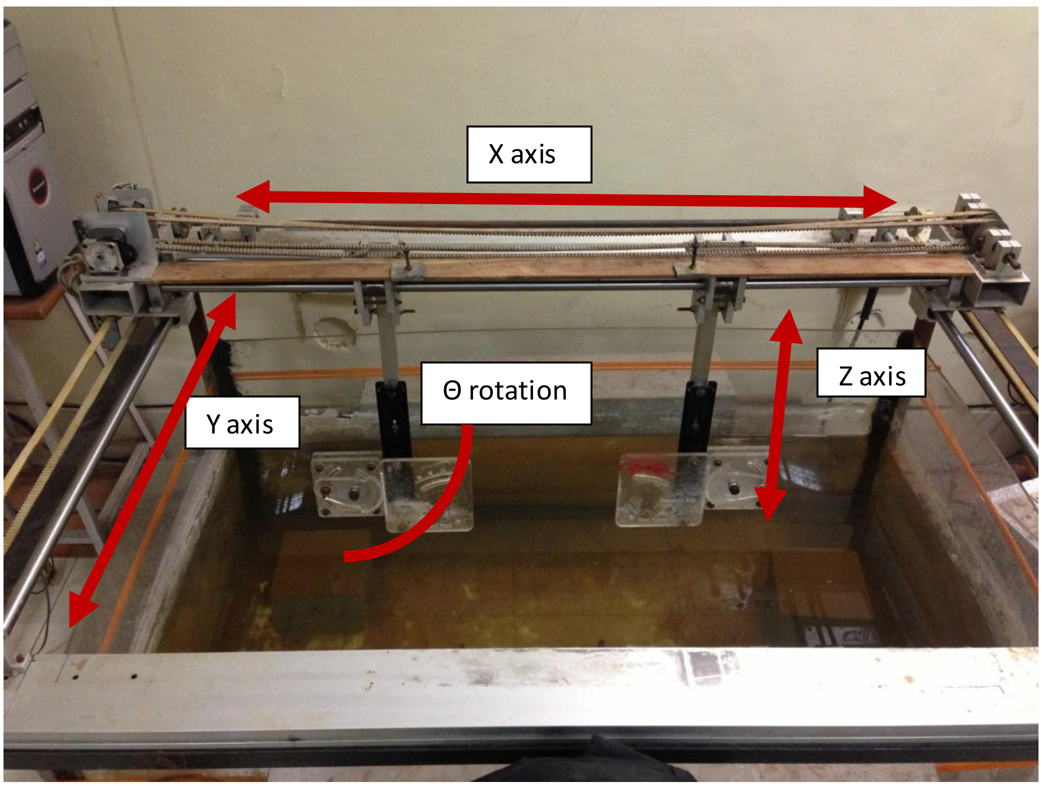


Figure 4.7: Four axis scanning set up

4.2.6 Water tank

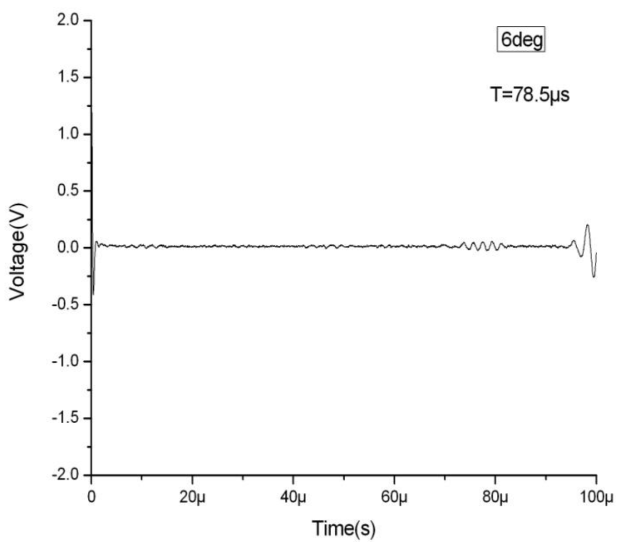
Water tank used in the experiment is made up of Perspex sheet with dimensions of is 120cm x 75cm x 50cm. Pipe is placed under the transducers for scanning which immersed in water. Suitable supporting arrangements are done for pipe. A V-block has been made on which the pipe is supported during testing.

4.3 SELECTION OF OPTIMUM FREQUENCY AND MODE

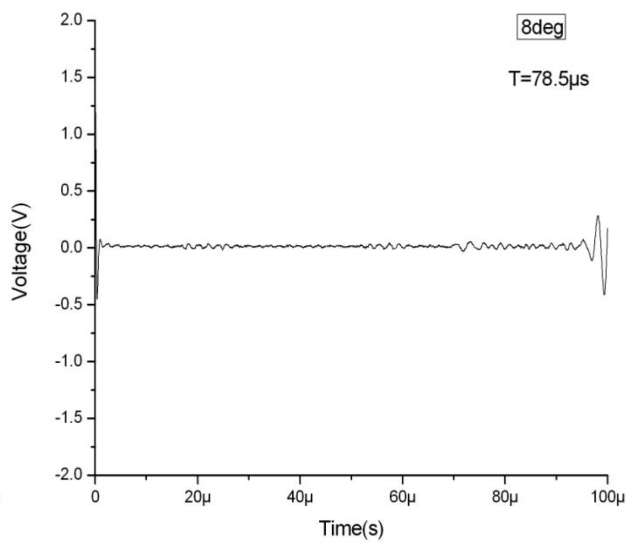
1MHz and 0.5MHz frequency transducers have been selected for performing the experiment. These transducers correspond to good signal fidelities and are commercially available. Transducers are mounted on the holder. Other ends of the transducers are attached to the transmitter/receiver connector through a cable in pulser/receiver generator. These holders can move from 0° to 30° angles. In the holders transducers and specimen (pipe) are kept under submerged condition. Aligned probes are placed above the pipe for testing. Through transmission method is used for ultrasonic testing. For placing the probes at a suitable distance for non-contact monitoring of submerged pipe, pulse-echo testing has been done first. It is experimentally observed that if the gap between the probe and pipe is too large it results in loss of incident energy to water whereas smaller gaps result in near field effect and yields poor signal. From the PE signatures obtained water path of 40µs and scanning distance of 200mm has been fixed. So, suitable distance has been selected for testing. The transducers are driven by a pulser/receiver system with maximum gain of 66db and maximum input voltage of 475V.

4.3.1 Selection of mode with 0.5MHz frequency

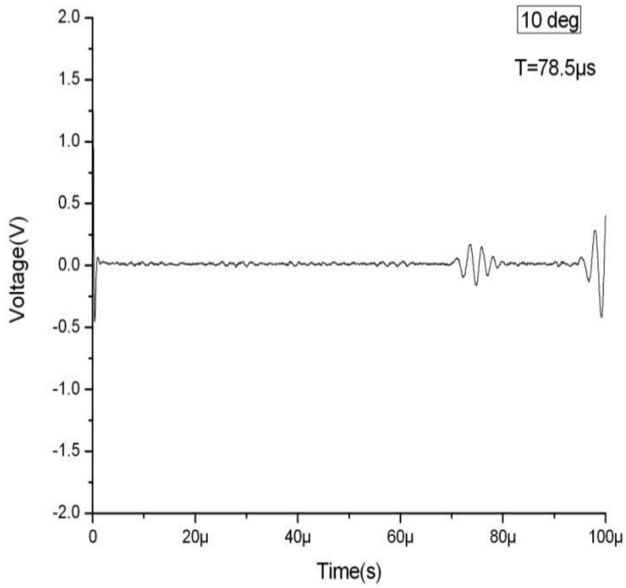
For selecting mode, experiment is performed at different probe angles. To avoid any bias in the experiment, P-R settings were kept constant during this study. Scanning distance 200mm and water path of 40µs for both probes has been used. Using through transmission method of scanning for immersed pipe following signatures are obtained at different angles of incidence.



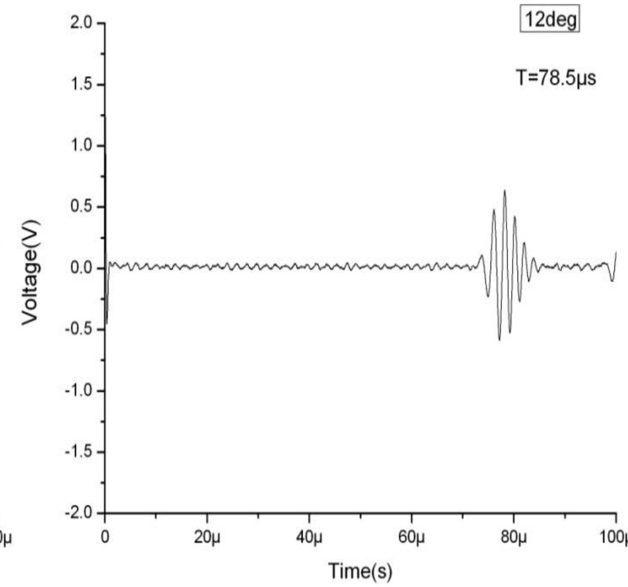
(a)



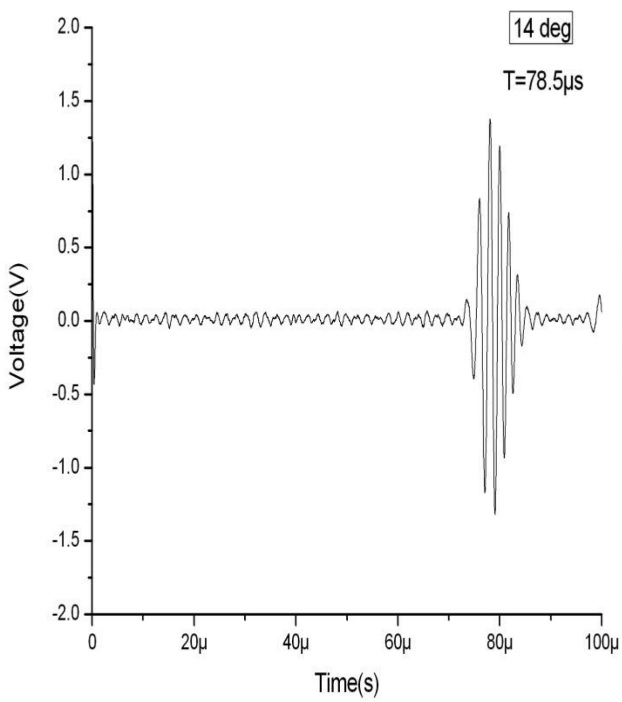
(b)


10 deg
T=78.5μs
Voltage(V)
Time(s)

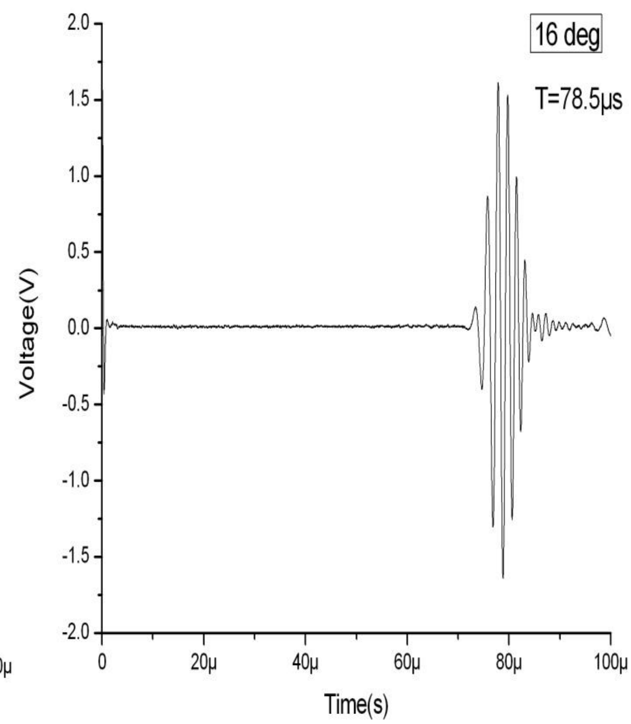
(c)


12deg
T=78.5μs
Voltage(V)
Time(s)

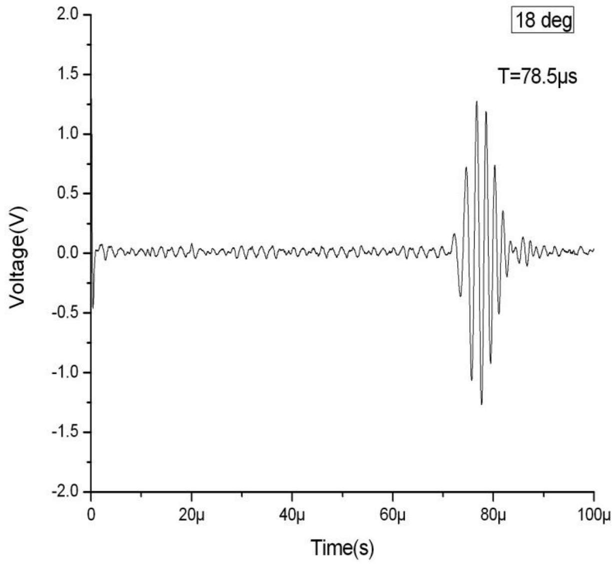
(d)


14 deg
T=78.5μs
Voltage(V)
Time(s)

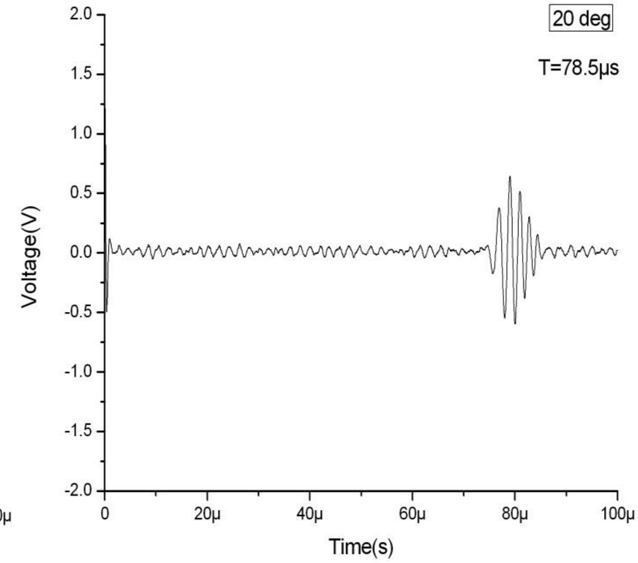
(e)


16 deg
T=78.5μs
Voltage(V)
Time(s)

(f)



(g)



(h)

Figure 4.8: PT signatures with 0.5MHz frequency at different angles of probe

In the above **Figure 4.8** 16° angle of incidence of probes yields a clear and sharp signal. So this angle has been used for further studies with 0.5MHz frequency. The mode near 79μs with 16°angle has been taken for studying the damage detection in pipes.

In **Figure 4.9** it is clear that at 16°angle there is maximum voltage amplitude. The signal obtained at this angle is significant and sharp as compared to other angles. Hence change in signal due to the presence of defect can be easily noticed.

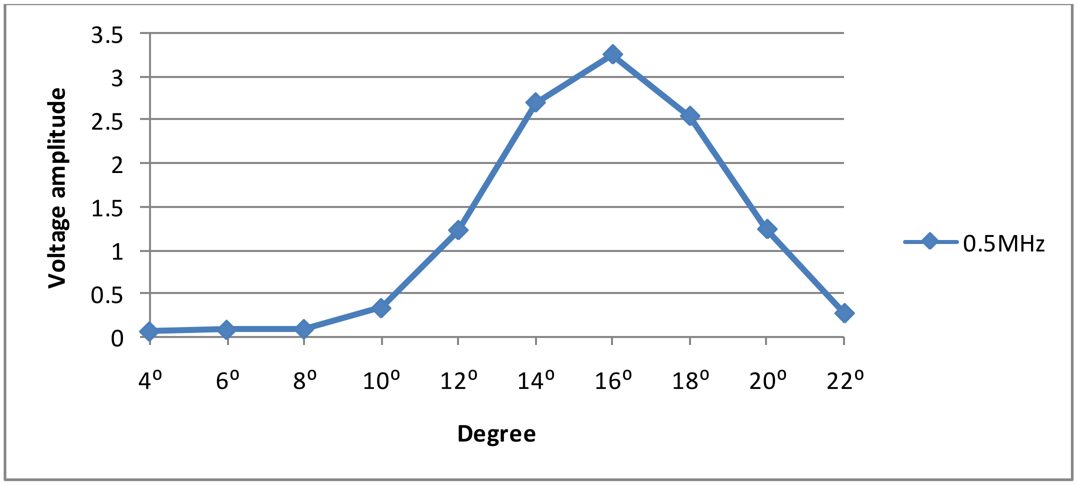
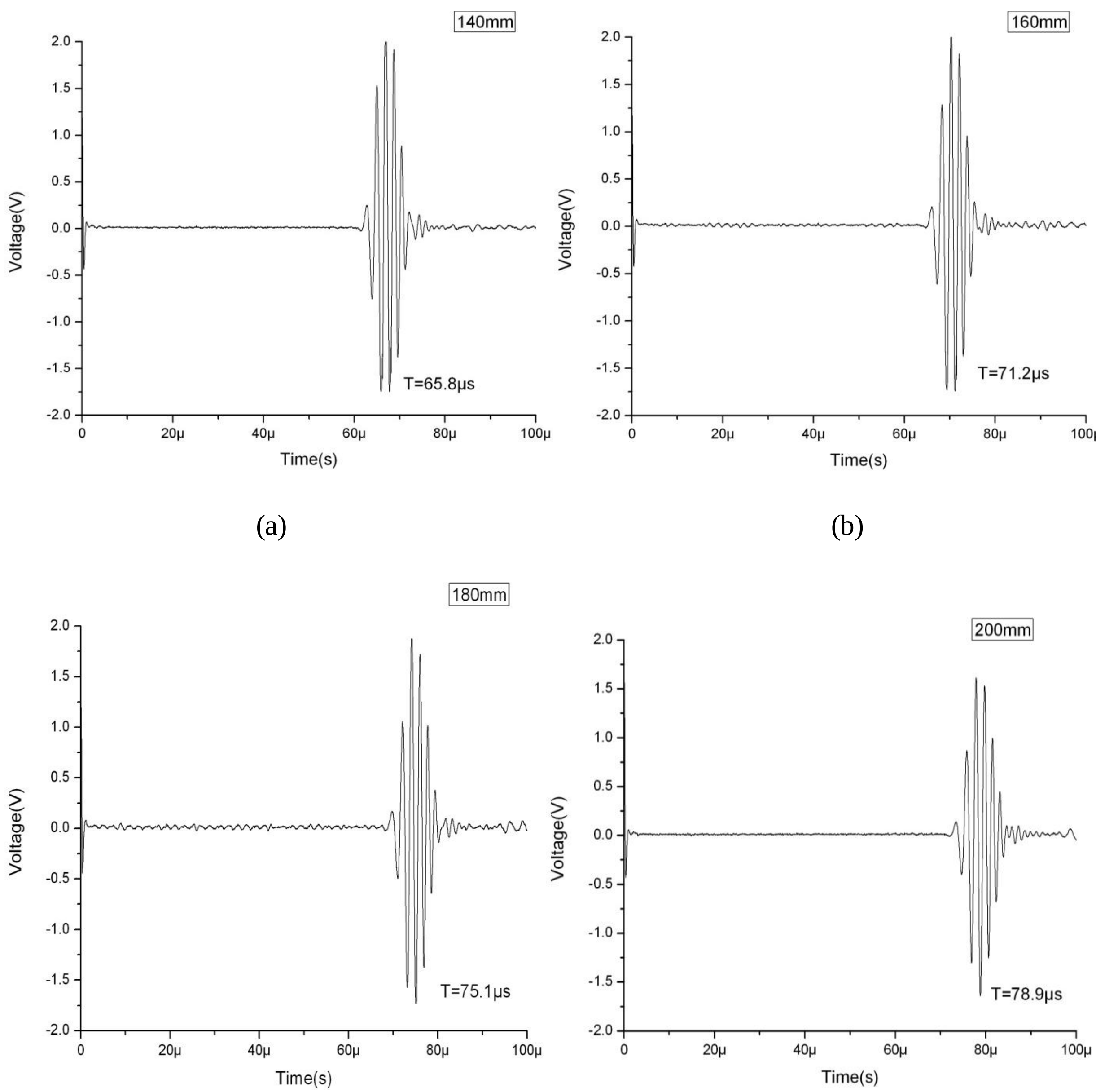


Figure 4.9: Peak to peak voltage values for different angles of probe

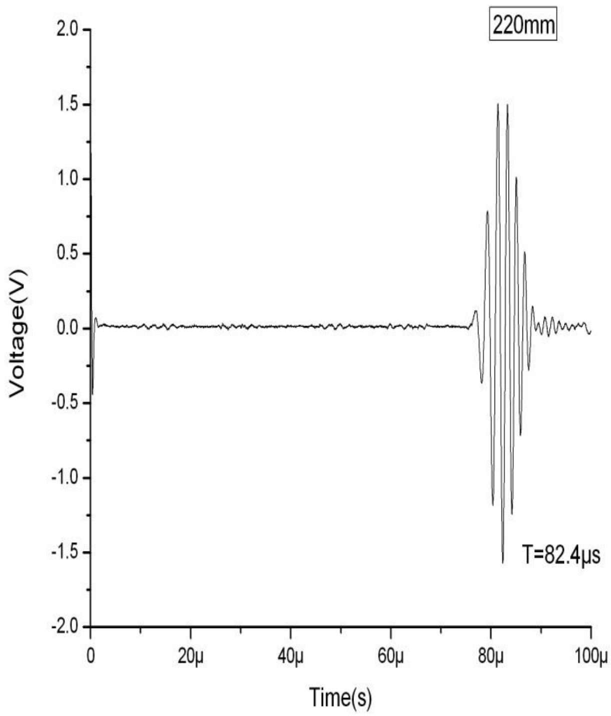
4.3.2 Varying propagation distance at selected frequency and mode

Propagation distance (PD) is varied by moving the transducers along the axis. In this the signatures were taken between the ranges of 140mm to 260mm with gap of 20mm. This study has been undertaken to study the behavior of the mode for varying propagation distance and to determine the optimum propagation distance to be used for further experimental investigations. By varying propagation distance it is also confirmed that the signal obtained maintains the shape and fidelity. PT signatures obtained by varying propagation distance are shown in figure 4.10.

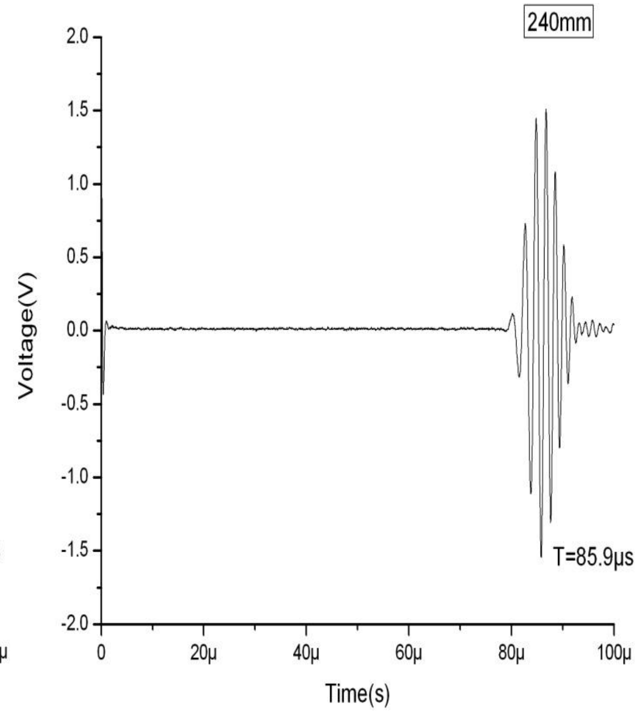


(a) (b)

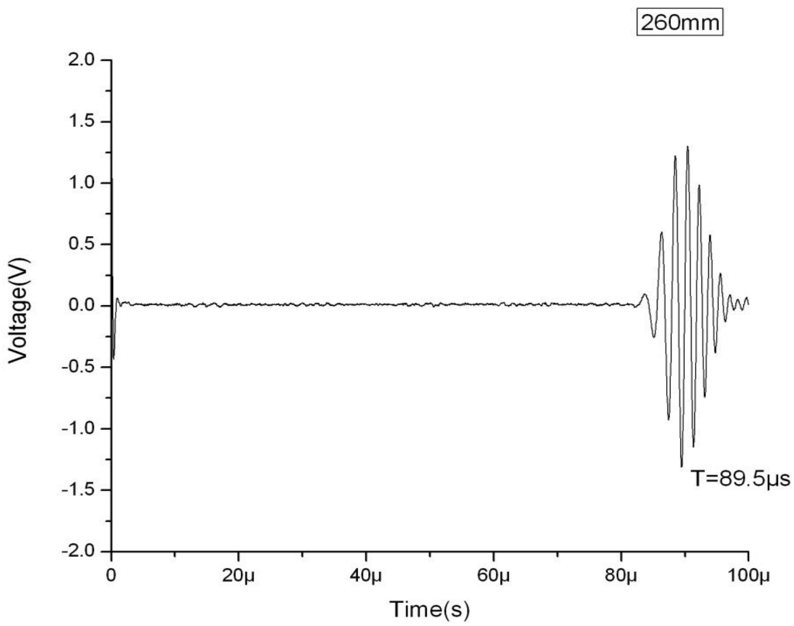
(c) (d)



(e)



(f)



(g)

Figure 4.10: PT signatures by varying distance at 0.5MHz

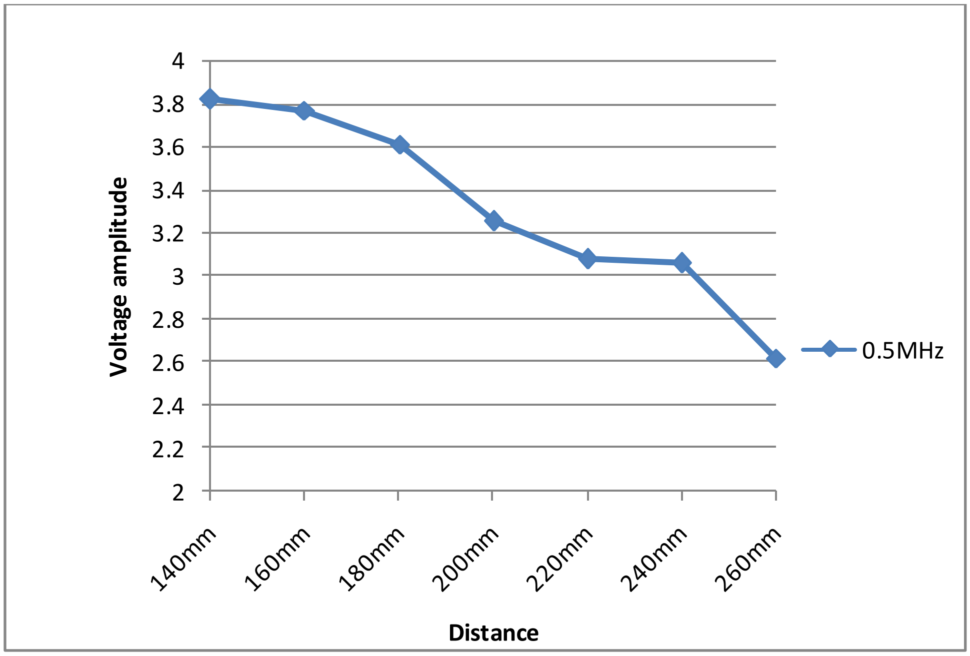


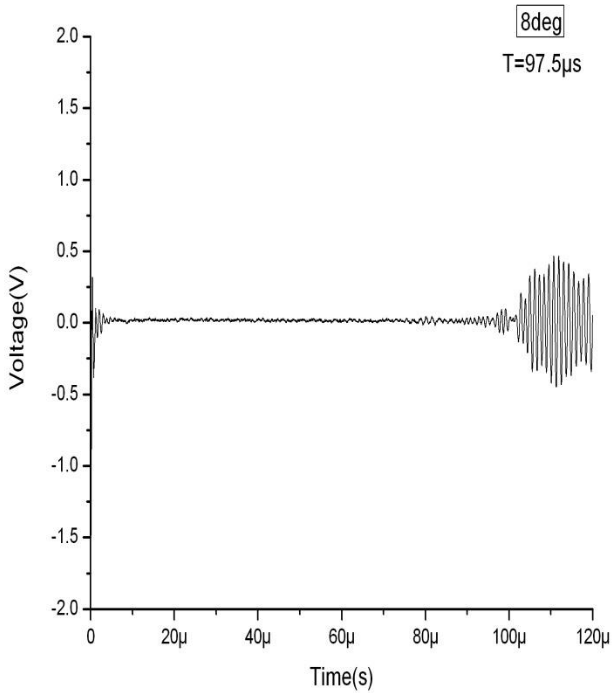
Figure 4.11: Peak to peak voltage at varying distance using 0.5 MHz

From the **Figure 4.11** it is clear that there is drop in voltage amplitude as the propagation distance increases because due to the increase in distance between transmitter and receiver probes more energy loss take place due to material attenuation and leakage of energy takes place into.

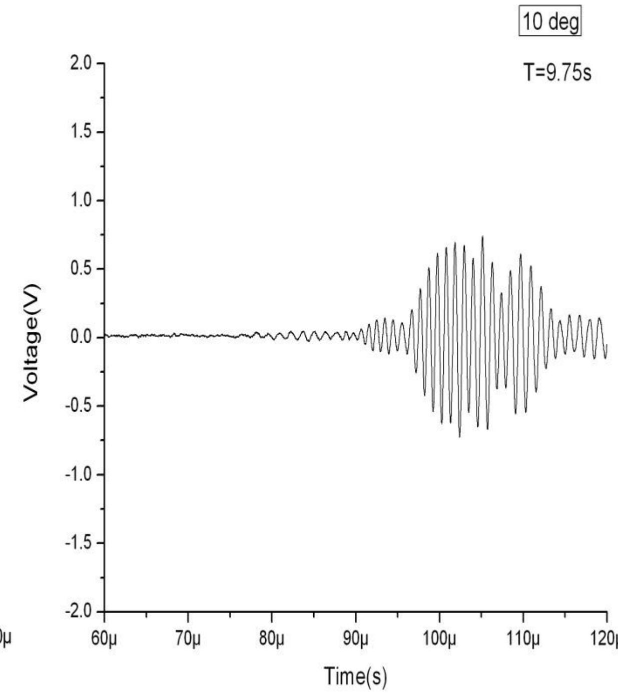
Hence it is practically figured out that at 16^o degree of angle peak retains its character and is suitable for finding out the defects in pipes at 0.5 MHz frequency. Also the guided wave mode at 16^o has clear and high peak to peak signal amplitude. To obtain optimum frequency and mode of excitation, modeling of 4mm thick steel pipe has done in DISPERSE. Theoretical matching of these experimental results has been done by using DISPERSE software. As discussed later in this chapter.

4.4 SELECTION OF MODE FOR 1MHz FREQUENCY

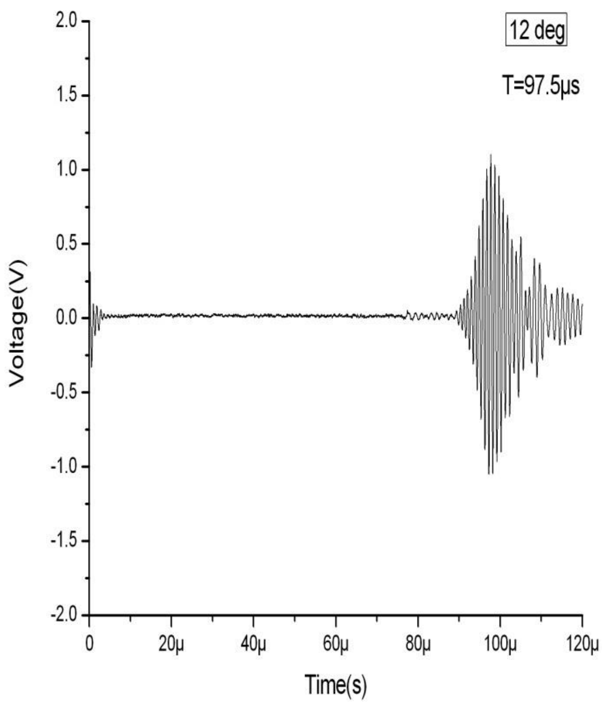
As explained earlier, in section 4.2 similarly 1MHz frequency transducers are used for finding the angle of incidence of guided waves. Distance for scanning of pipe is initially kept at 200mm and water path 40µs was adjusted using PE settings. Experiment is performed for finding the proper mode at different angles using through transmission method. Angles of incidence are varied from 0 to 22 degree by changing from the holder and PT signatures which are recorded at different angles with 1MHz frequency which are shown in **Figure 4.12.**

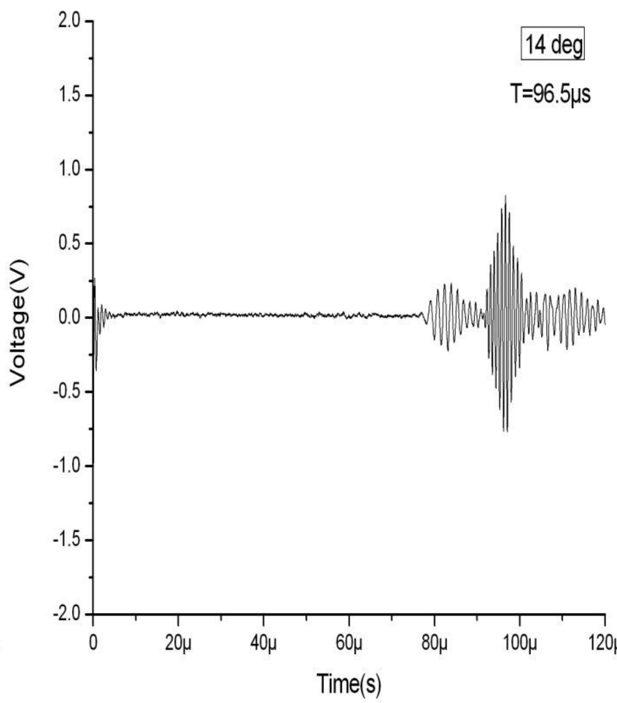


(a)

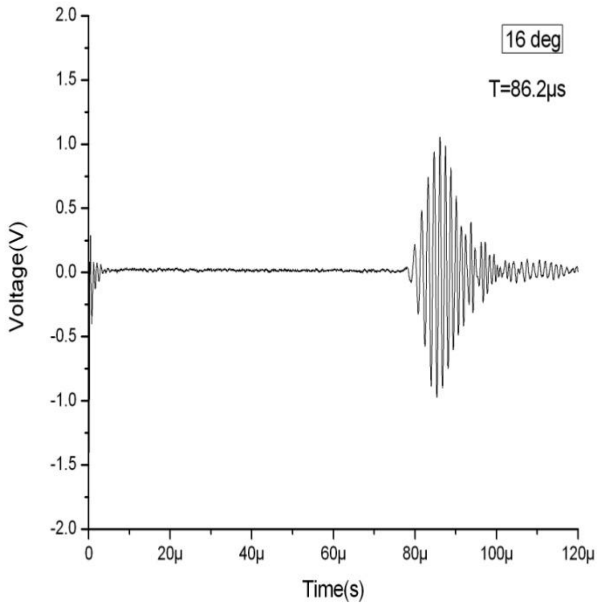


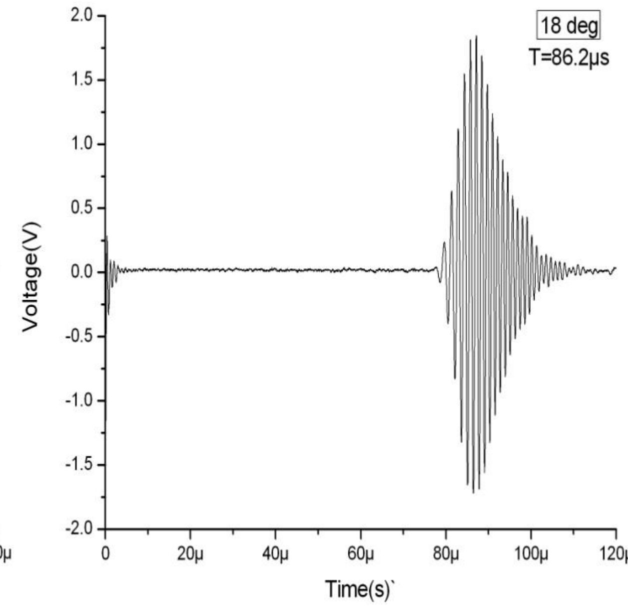
(b)



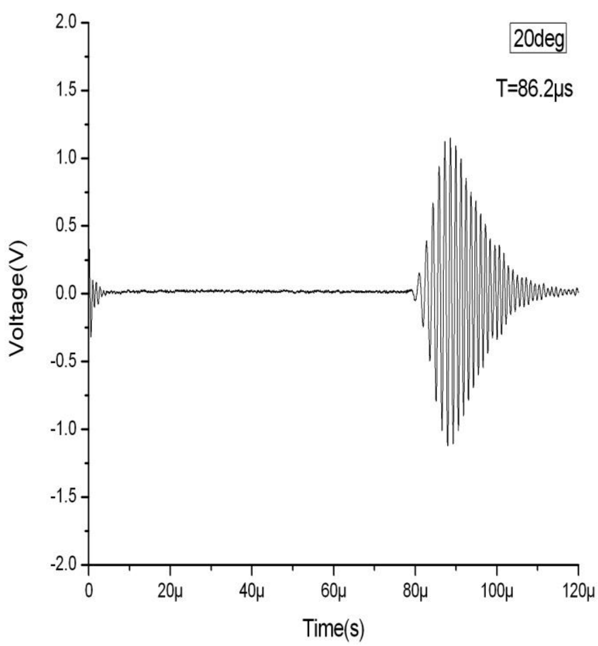


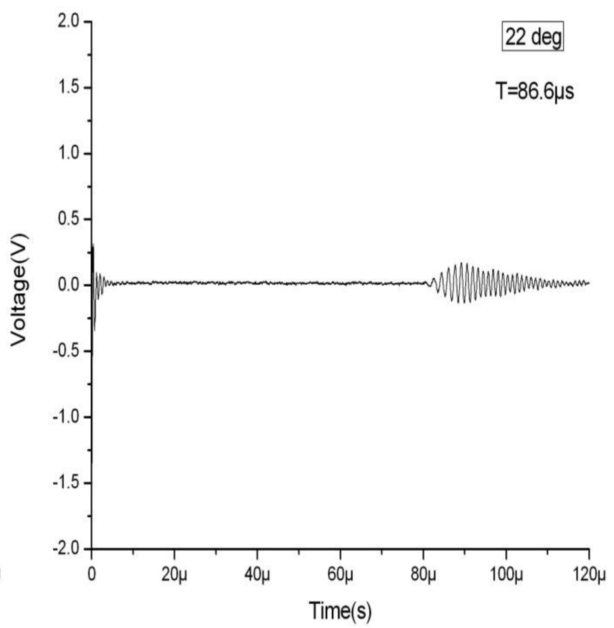
(c) (d)





(e) (f)





(g) (h)

Figure 4.12: PT signatures at different angles with 1MHz

PT signatures obtained for 1MHz frequency shows distinct modes, at 12⁰ and 18⁰ angle. The TOF at these angles are also different which shows availability of two different modes at these two angles of incidence.

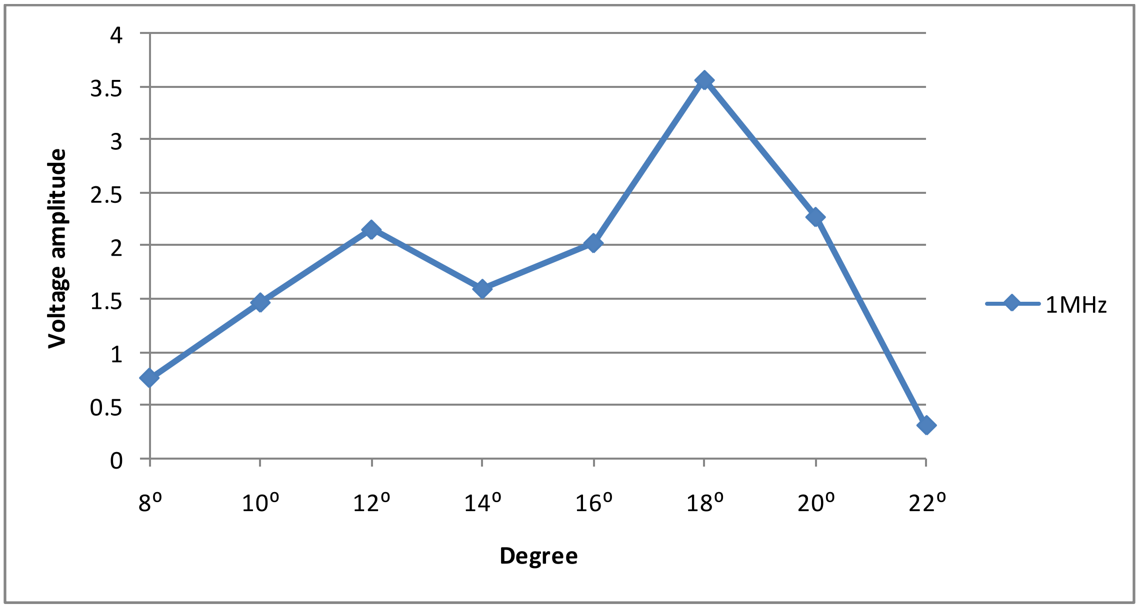
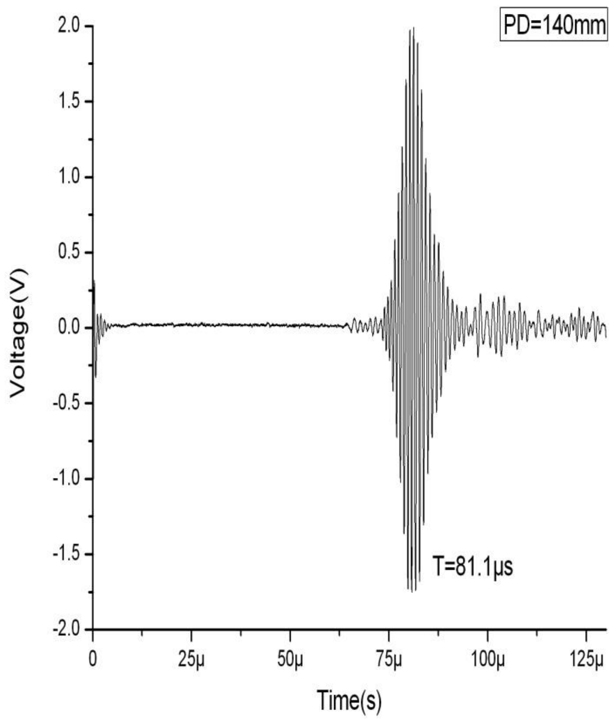


Figure 4.13: Peak to peak voltage at different angles

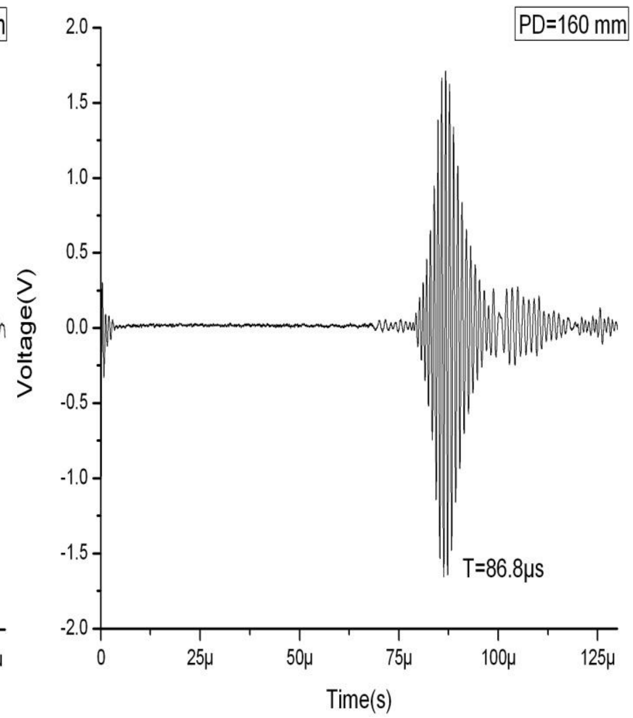
In **Figure 4.13** it is clear that at 18⁰angle the guided waves has sharp and clear signal. However at12⁰ angle the mode generated is relatively less sharp and has relatively low peak to peak voltage. Both these modes have been further investigated into for their suitability for damage detection.

4.4.1 Varying propagation distance for selected mode with 1MHz frequency

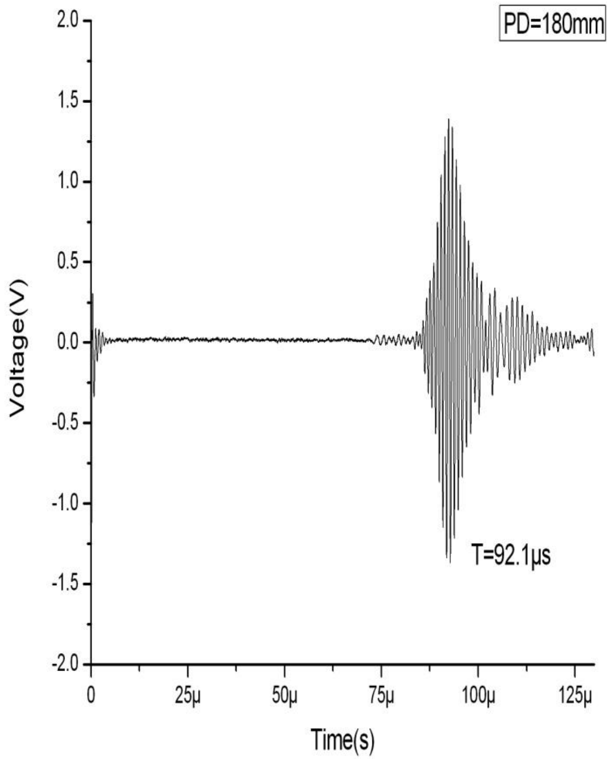
Distance has varied to establish the suitability of the selected modes for variable distance of propagation. Propagation distance is increased from 140mm to 260mm to check the propagation characteristics for selected mode.PT signatures at 12⁰angle of incidence by varying the propagation distance are shown below in **Figure 4.14.**


PD=140mm
T=81.1μs
Voltage(V)
Time(s)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
25μ
50μ
75μ
100μ
125μ

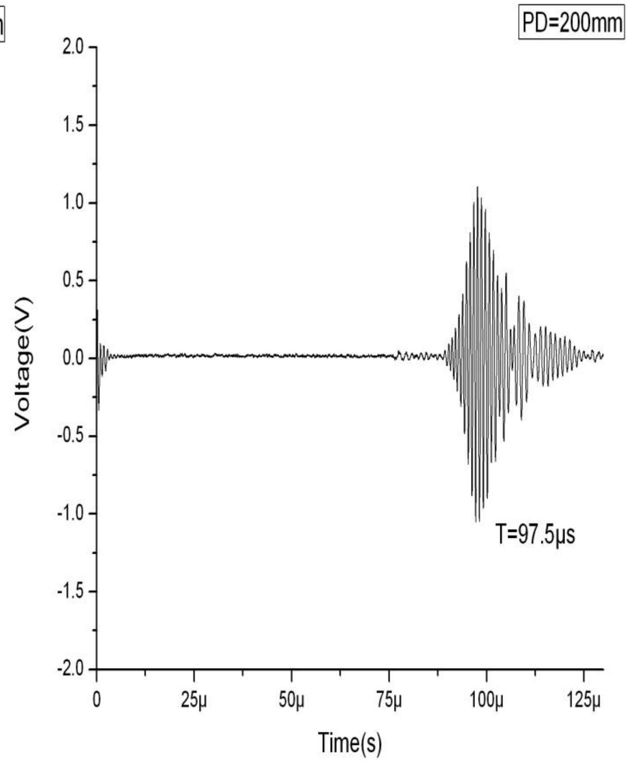
(a)


PD=160 mm
T=86.8μs
Voltage(V)
Time(s)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
25μ
50μ
75μ
100μ
125μ

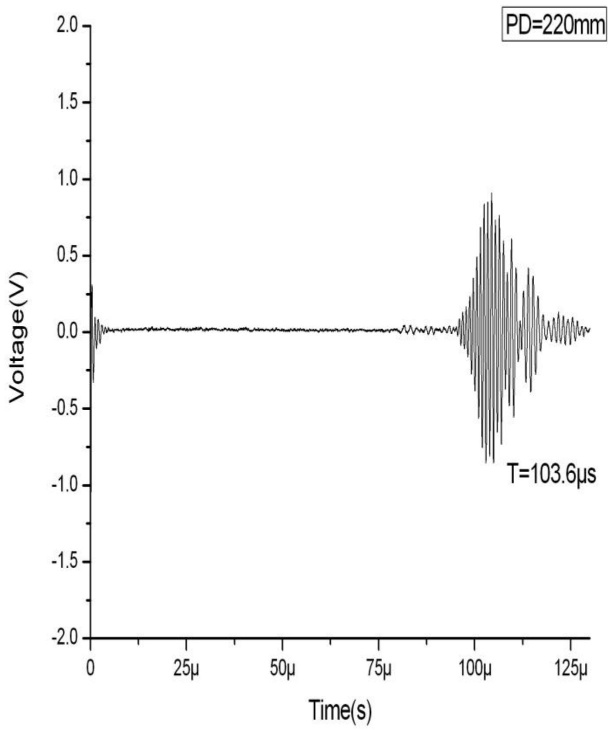
(b)


PD=180mm
T=92.1μs
Voltage(V)
Time(s)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
25μ
50μ
75μ
100μ
125μ

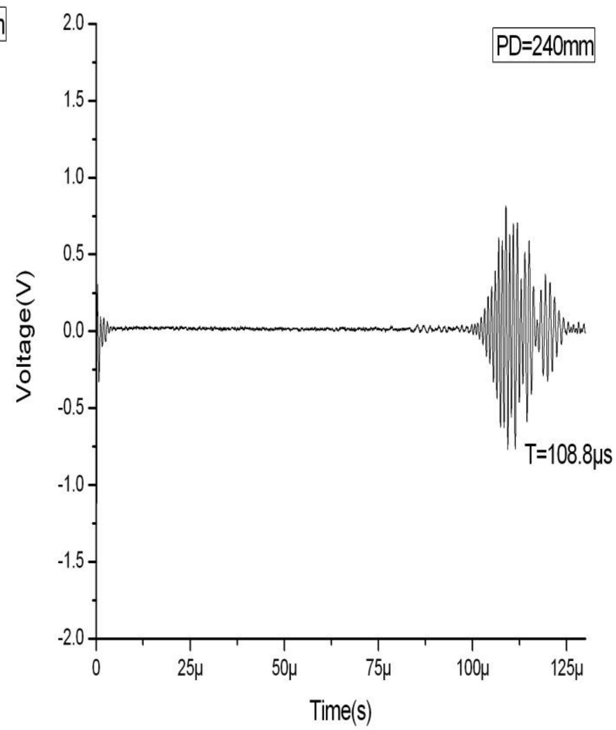
(c)


PD=200mm
T=97.5μs
Voltage(V)
Time(s)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
25μ
50μ
75μ
100μ
125μ

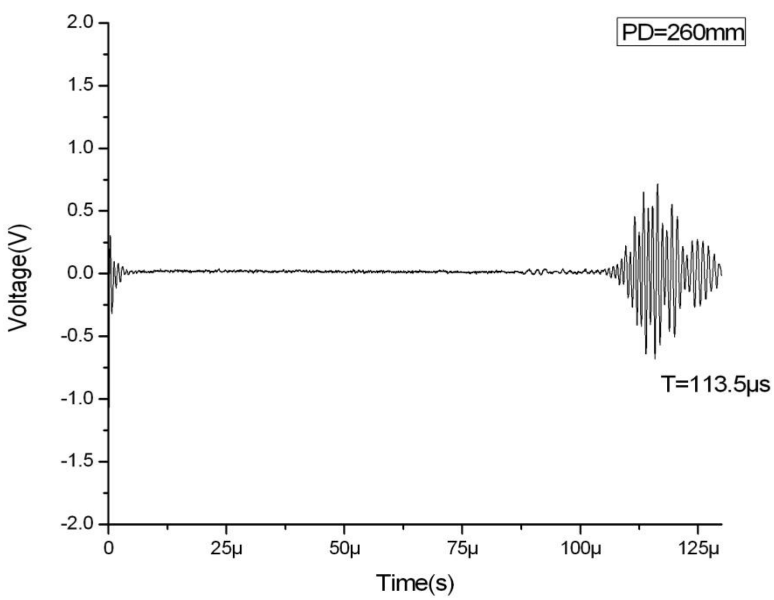
(d)



(e)



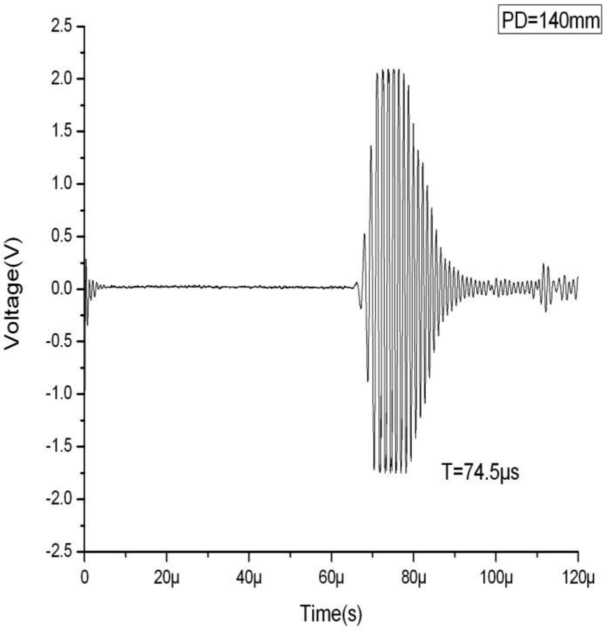
(f)



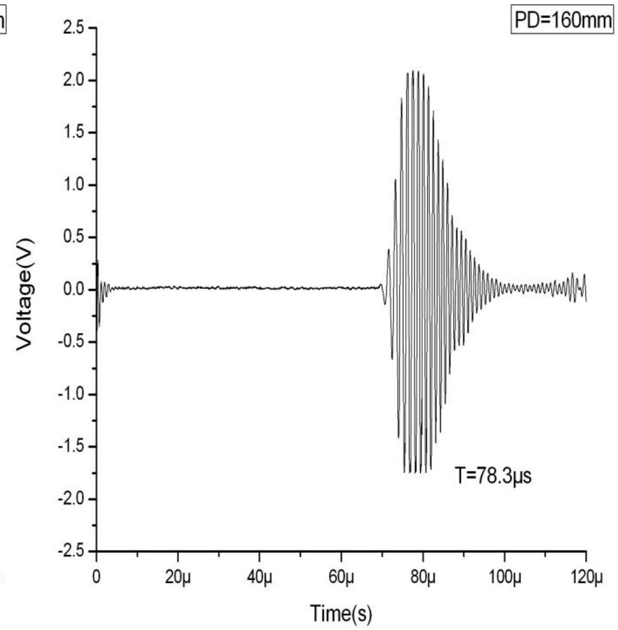
(g)

Figure 4.14: PT signatures by varying distance with 1.0MHz at 12^{o} angle of incidence

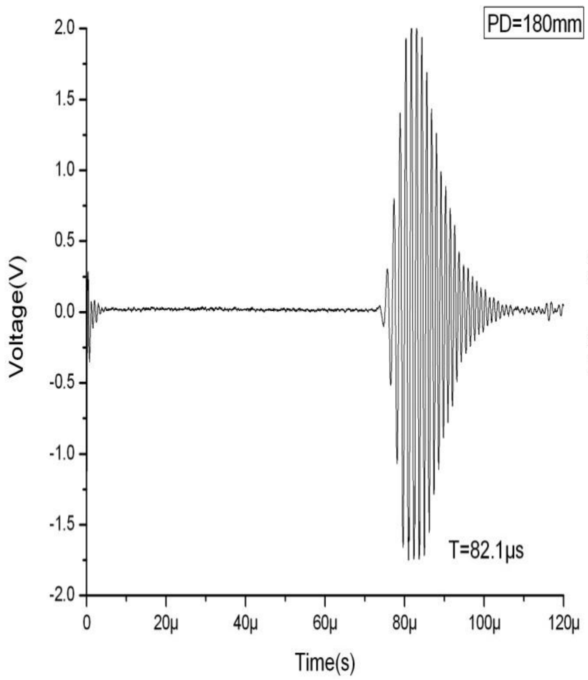
At 18^{o}angle there exists maximum peak to peak voltage. With the same setting PT signatures for varying distance at 18^{o}angle with 1MHz frequency are shown in **Figure 4.15.**


PD=140mm
T=74.5µs
Voltage(V)
Time(s)

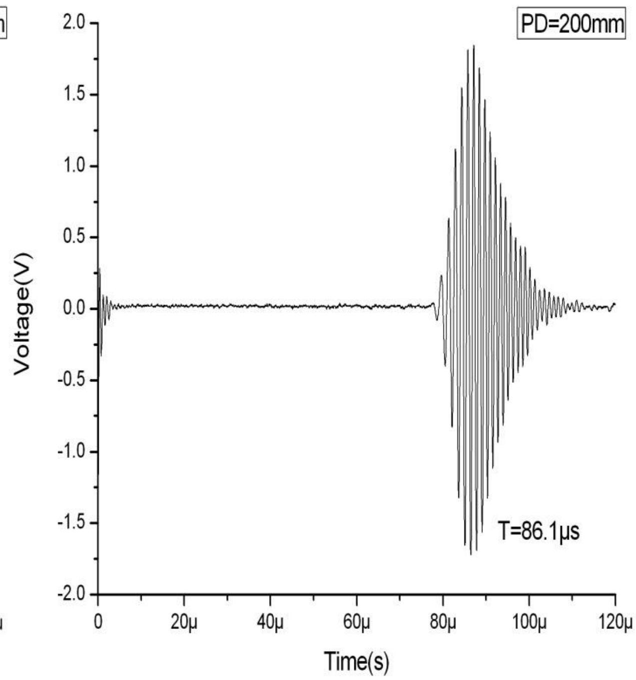
(a)


PD=160mm
T=78.3µs
Voltage(V)
Time(s)

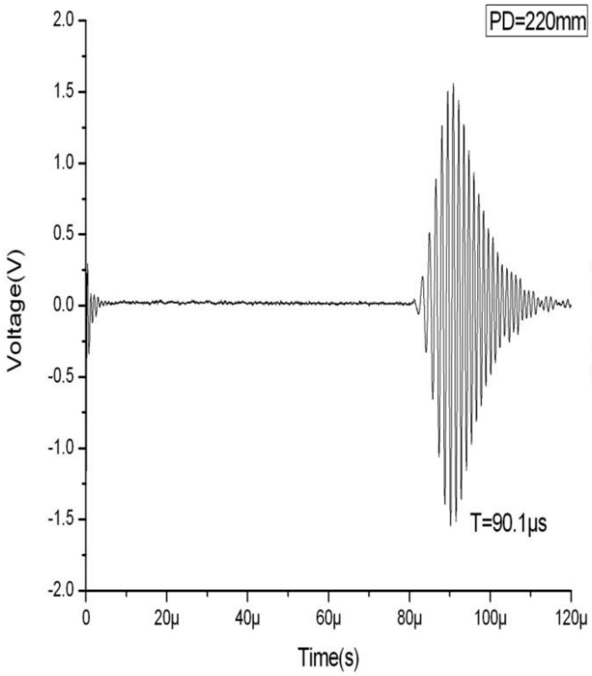
(b)


PD=180mm
T=82.1µs
Voltage(V)
Time(s)

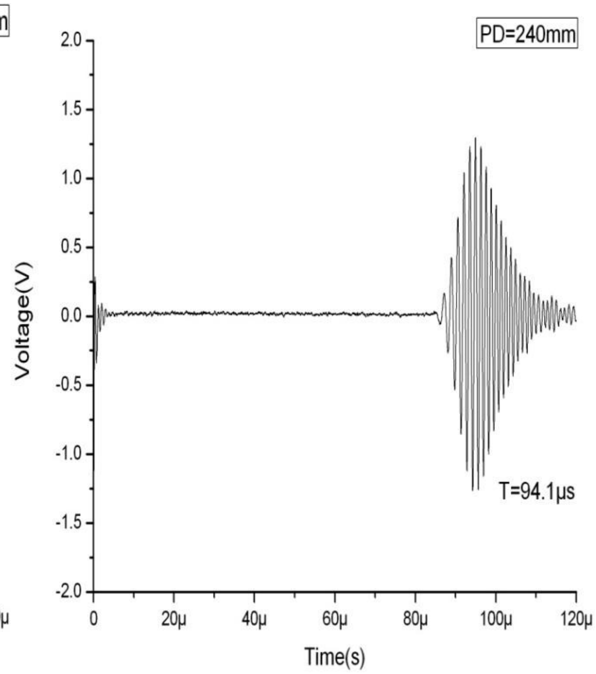
(c)


PD=200mm
T=86.1µs
Voltage(V)
Time(s)

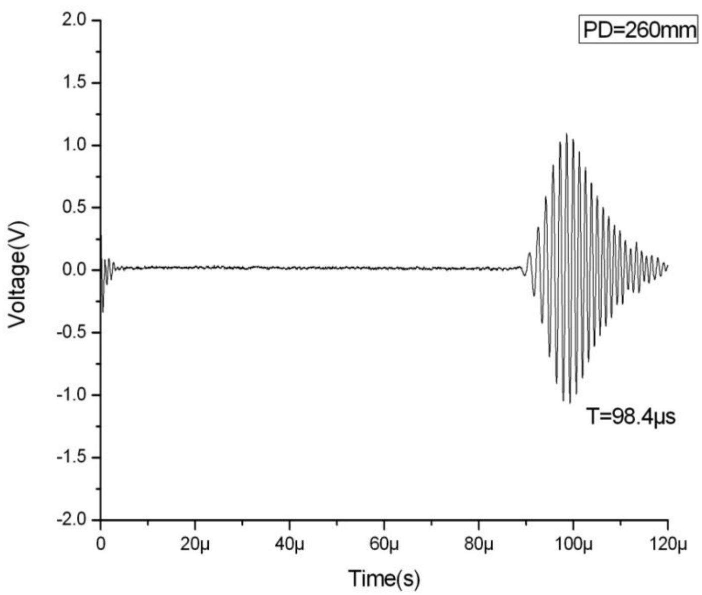
(d)



(e)



(f)



(g)

Figure 4.15: PT signatures by varying distance with 1.0MHz at 18^o angle of incidence

This mode is found to be more consistent as compared to the signal obtained at 12^o angle as far as the variation in propagation distance is concerned. This mode shows comparatively less dispersion in time as compared to the other mode at 12^o. Thus, it can be concluded that at 1 MHz frequency, at angle of incidence 12^o and 18^o yield good signal and these two modes have the potential to be further investigated for their suitability for damage detection submerged pipe problems

4.5 IDENTIFICATION OF MODE USING DISPERSION CURVE FOR PIPE

Important property of the guided waves is dispersion which is dependent on propagation speed that is why these waves are called dispersive waves. At a given frequency multiple modes can exist each having its own wave speed. Different wave speed corresponds to different wave modes of the propagating waves. To identify and the selected modes modeling of 4mm thick hollow steel pipe was done in DISPERSE. Disperse curves for phase velocity and group velocity were obtained as shown in **Figure 4.16, 4.17**. An idea of mode at a particular time can be obtained from these curves. From dispersion curves we can obtain the phase velocity and group velocity of particular mode. So knowing the distance and time velocity at a particular point can be calculated and compared with velocities obtained from dispersion curves.

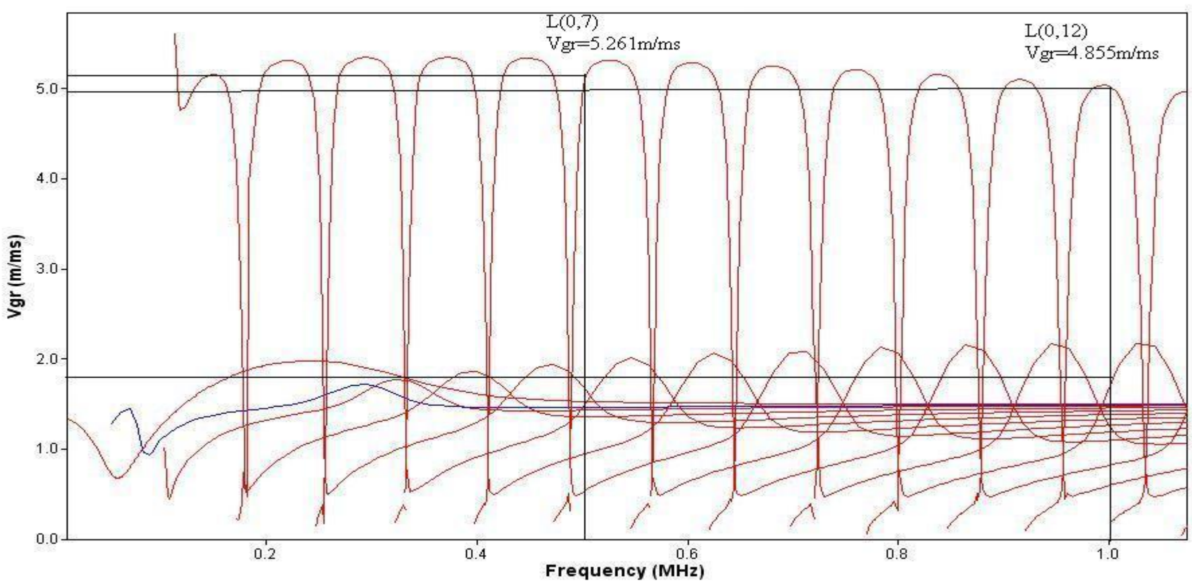


Figure 4.16: Group Velocity Dispersion curves for longitudinal waves propagation of 4mm thick pipe.

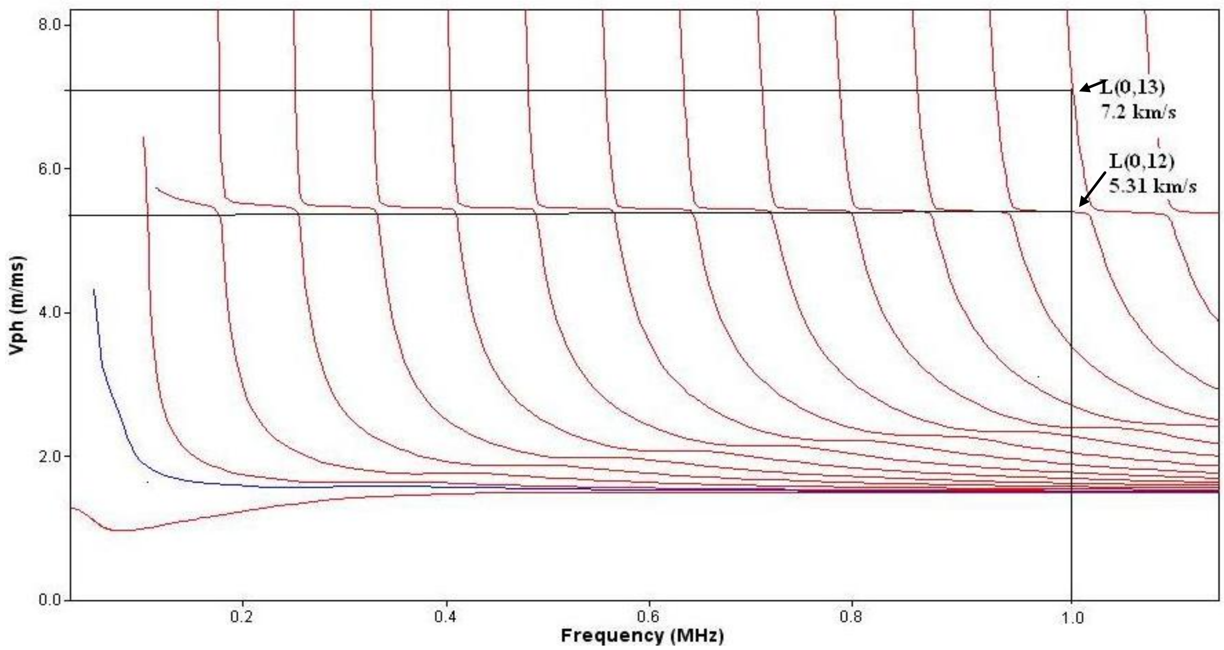


Figure 4.17: Phase Velocity Dispersion curves showing phase velocity of different modes.

A From the value of phase velocity we can also check out angles that are calculated by Snell's law for 0.5 MHz frequency

$$\frac{\text{Sin } A_1}{V_1} = \frac{\text{Sin } 90^{\circ}}{V_2}$$

V_1 is velocity of wave in water = 1.5 km/s

V_2 is velocity of wave in steel = 5.6 km/s corresponding to L (0,7) mode.

A_1 (Incidence angle) = $\text{Sin}^{-1}\left(\frac{V_1}{V_2}\right)$

$A_1 = \text{Sin}^{-1}\left(\frac{1.5}{5.6}\right)$

$A_1 = 15.6^{\circ}$

Similarly for 1MHz the angle of incidence comes out to be approximately 12^o and 18^o respectively for modes L(0,13) and L(0,12) modes.

Similarly, for finding group velocity at these modes can be evaluated as per the relation:

$$V_{gr} = \frac{PD}{(TOF - WP)}$$

$$V_{gr} = \frac{200}{(83.3 - 40)} = 4.623 \text{m/ms}$$

Where PD= Propagation distance

TOF= Time of flight =as noted from the PT signature

WP=Water path= 40 µs

Similarly group velocity for 0.5MHz can also be calculated. Group velocities values calculated theoretically matches with the practical one thus it shows that these modes are suitable for further study.

4.6 RESULTS AND DISCUSSIONS

In this chapter ultrasonic signatures have been recorded by exposing the immersed steel pipe at varied angles of incidence. From the results L (0, 7), L (0, 12) and L (0, 13) modes have been selected for further investigations. These modes have been selected because of signal fidelity and clarity of signal. Also these modes have reasonably high peak to peak voltage which is required so as to register a noticeable change when the propagating waves come across damage.

CHAPTER 5

DAMAGE DETECTION IN PIPES- SIMULATED DEFECTS

5.1 GENERAL

In this chapter the state of health of an immersed steel pipe has been ultrasonically evaluated. 0.5MHz and 1MHz frequency probes have been used to generate guided waves. Longitudinal guided waves have been generated by placing the transducers at selected angles of incidence under submerged condition. Healthy signal are recorded first and then by increasing damage signatures have been recorded.

Simulated defects in the form of machined notch and circumferential hole have been put on the specimen. Extent of these defects has been varied and corresponding signatures have been recorded to study the effect of these damages ultrasonically. Depth of the cut is increased circumferentially at same position step by step. To study the defects through transmission method has been used in this experiment.

5.2 ULTRASONIC IVESTIGATIONS-SIMULATED NOTCHES

Notches are induced in the middle of the pipe. Notch was made on lathe machine with grooving tool of 2mm width. The width of notch 2mm and depth of 3.5mm is induced in pipe step by step as shown in the **Figure 5.1**. Depth of notch is increased by 1mm each time after taking readings in PT mode at selected frequencies and modes. L(0,7), L(0,12) and L(0,13) modes has been used to detect the simulated defects. Signatures are obtained with notch defect and compared with the healthy signal of the pipe. Notch study is important as in most of the defects like corrosion, erosion etc mostly the cross section of the pipe is affected. Objective of this study is to understand the changes in ultrasonic transmitted signal with the change in cross sectional area.

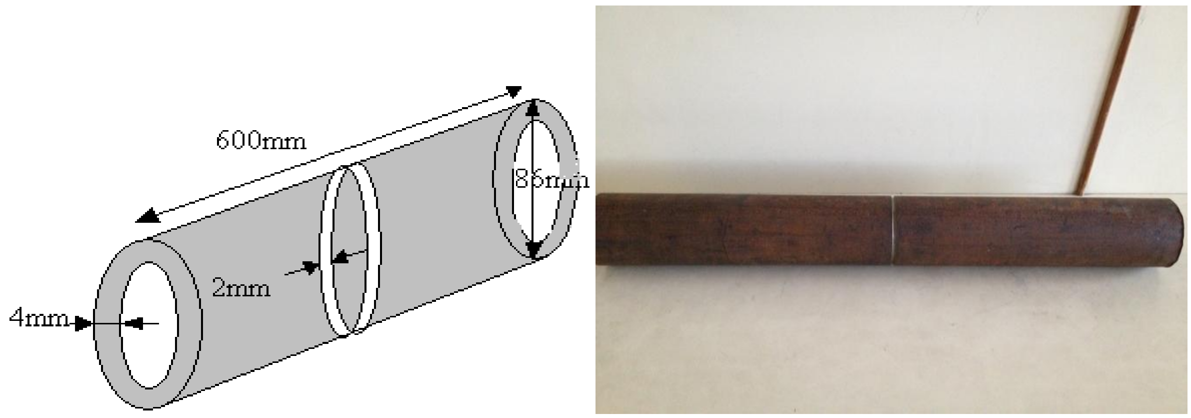


Figure 5.1: Dimensions of specimen

5.2.1 L(0,7) mode at 0.5MHz frequency

Ultrasonic pulse transmission signatures are recorded at all locations as shown in **Figure 5.2**. These locations are at a gap of 30^{o}. Signatures are obtained at all the locations around the circumference of the pipe. It is done to ensure whether at all locations fall in voltage amplitude is consistent or not due to presence of notch. It also ensures repeatability of results at different circumferential positions.

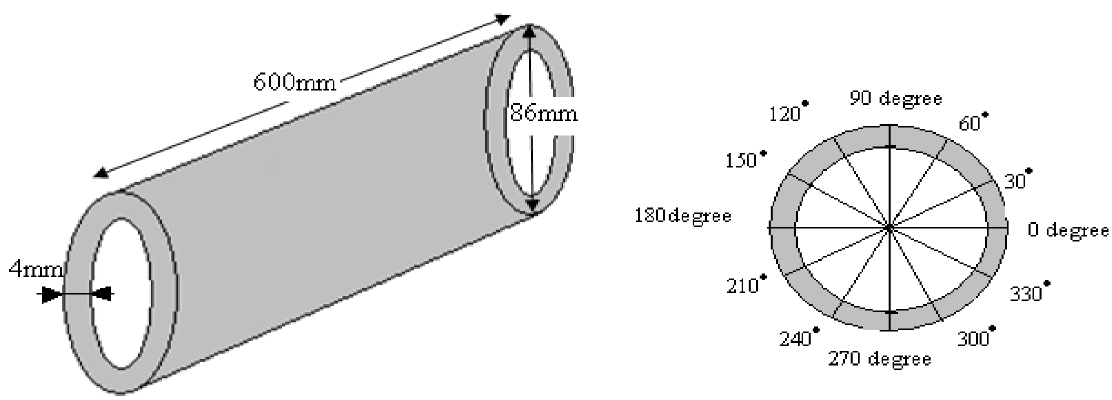
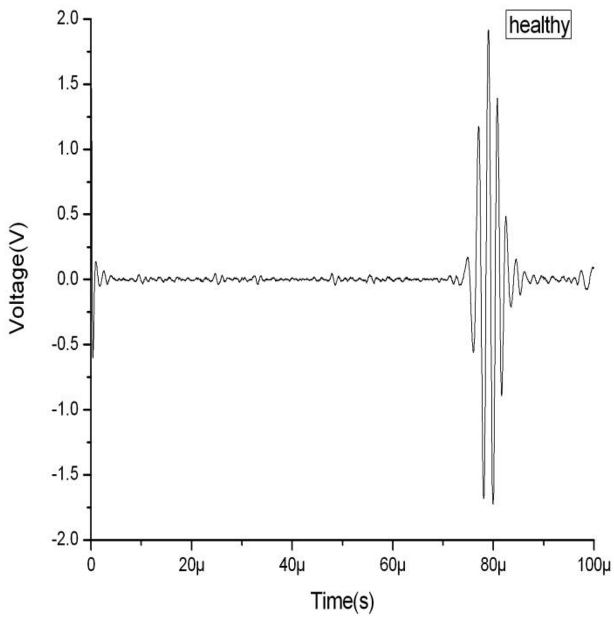
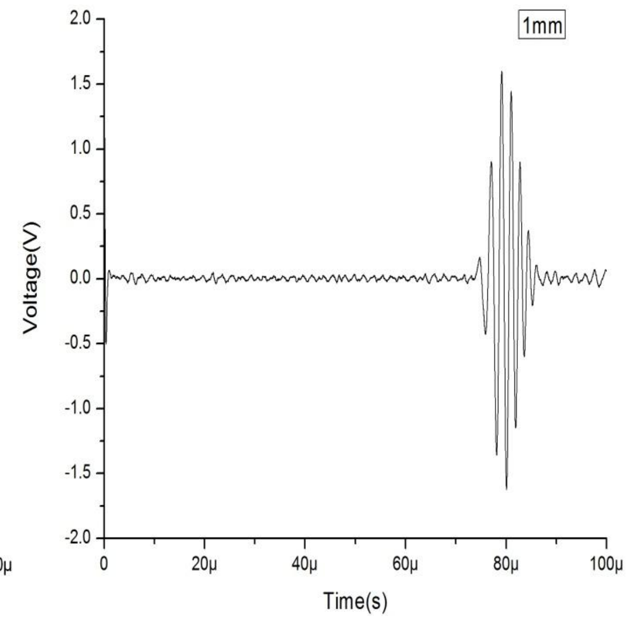


Figure 5.2: Shows different location around the circumference of pipe

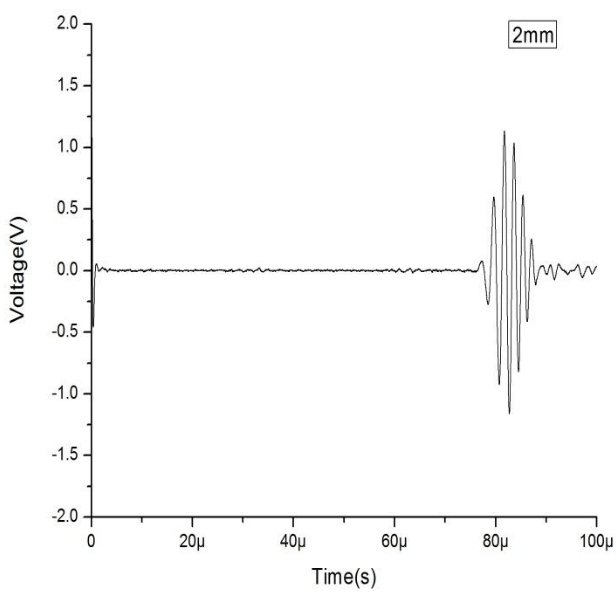
Healthy signatures of pipe with L (0, 7) mode and by increasing depth of notch signatures have been recorded. Propagation distance 200mm with water path of 40µs as calculated earlier has been taken. Maximum gain of 48db and voltage 475V has been used in this study for detecting notch defects. PT signatures recorded by using 0.5MHz frequency with L(0,7) mode by increasing depth of notch are as under shown in **Figure 5.3**



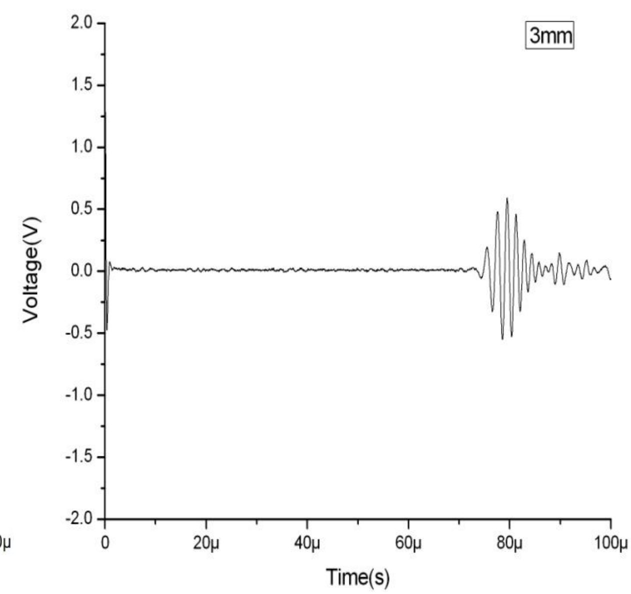
(a)



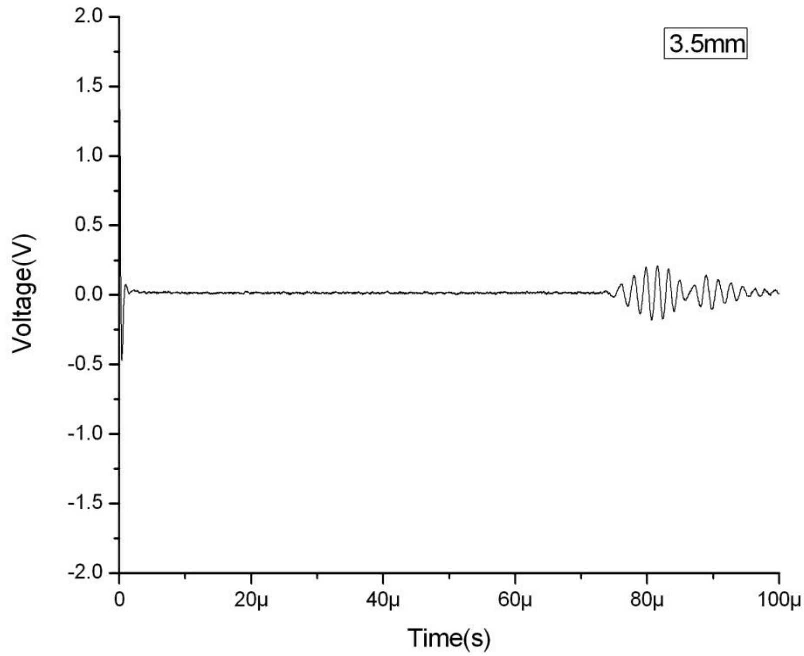
(b)



(c)



(d)



(e)

Figure 5.3: PT signatures using L(0,7) mode at 0.5MHz for (a) healthy pipe (b)notch depth 1mm (c) notch depth 2mm (d) notch depth 3mm (e) notch depth 3.5mm

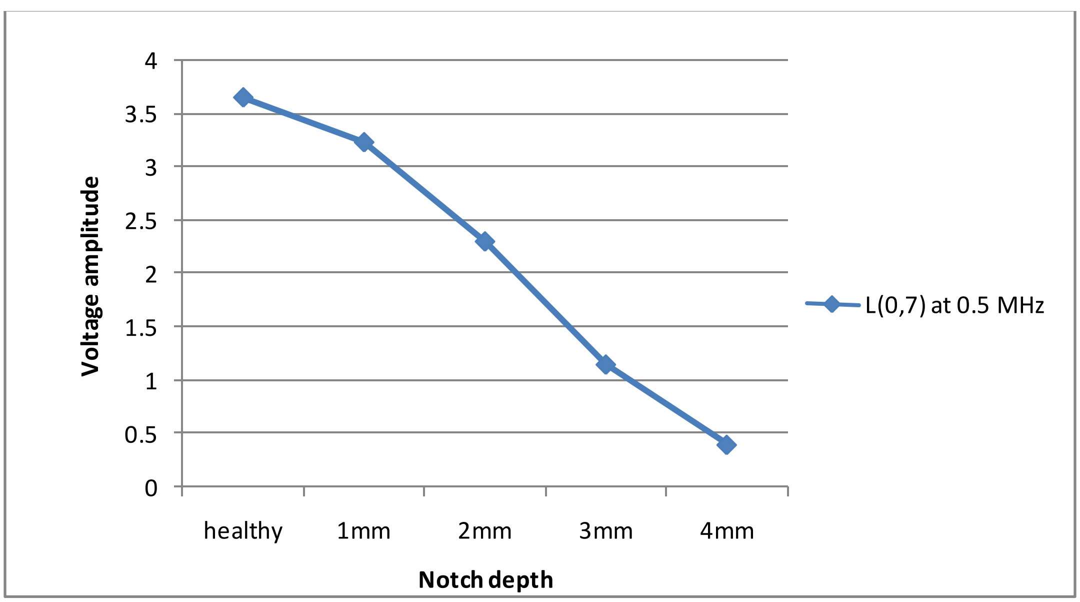


Figure 5.4: Peak to peak voltage for varying notch depth

From **Figure 5.3** it is observed that there is drop in ultrasonic signal as the depth of the notch increases. This drop in voltage value indicates the presence of notch when compared to healthy signal. Normalized voltage amplitudes with respect to healthy voltage are plotted in **Figure 5.5.**

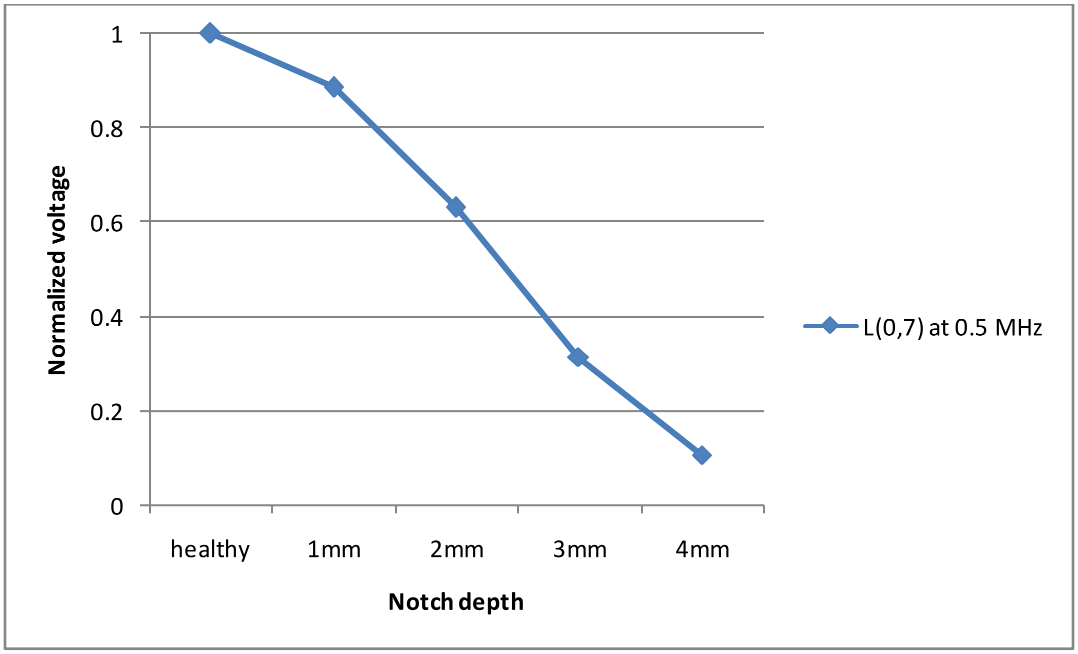


Figure 5.5: Normalized peak to peak voltages of PT signals at varying notch depth

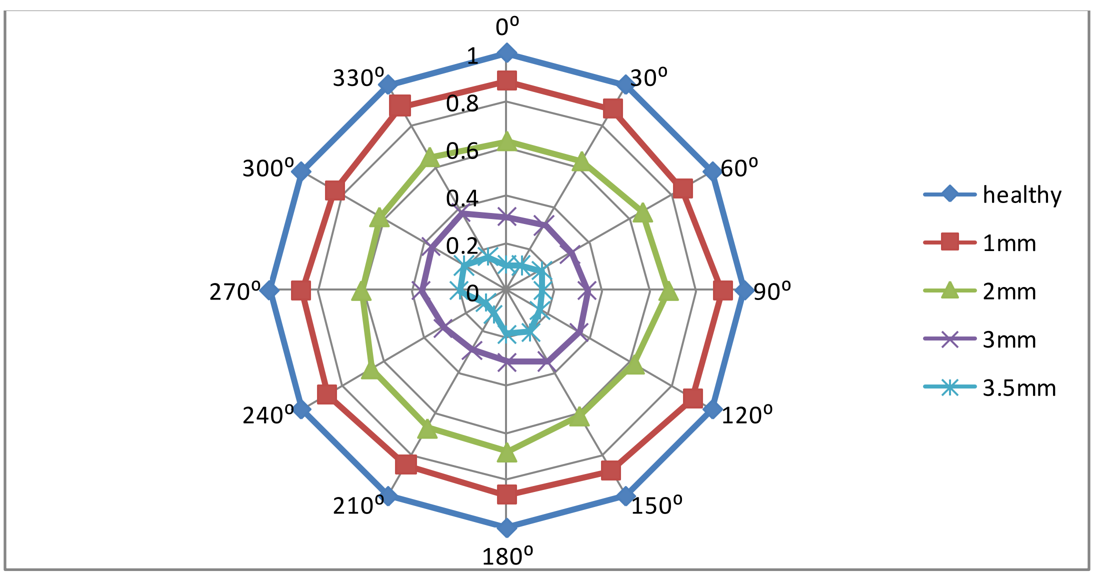


Figure 5.6: Circumferential normalized peak to peak voltage values at different notch depth

It is also noted out that there is sharp and consistent drop in voltage amplitudes as the depth of notch increases **(Figure 5.5)**. Same trend is observed in **Figure 5.6** at all circumferential locations of the pipe. Increasing depth of the notch causes less transmission of signal resulting in attenuation of the signal strength.

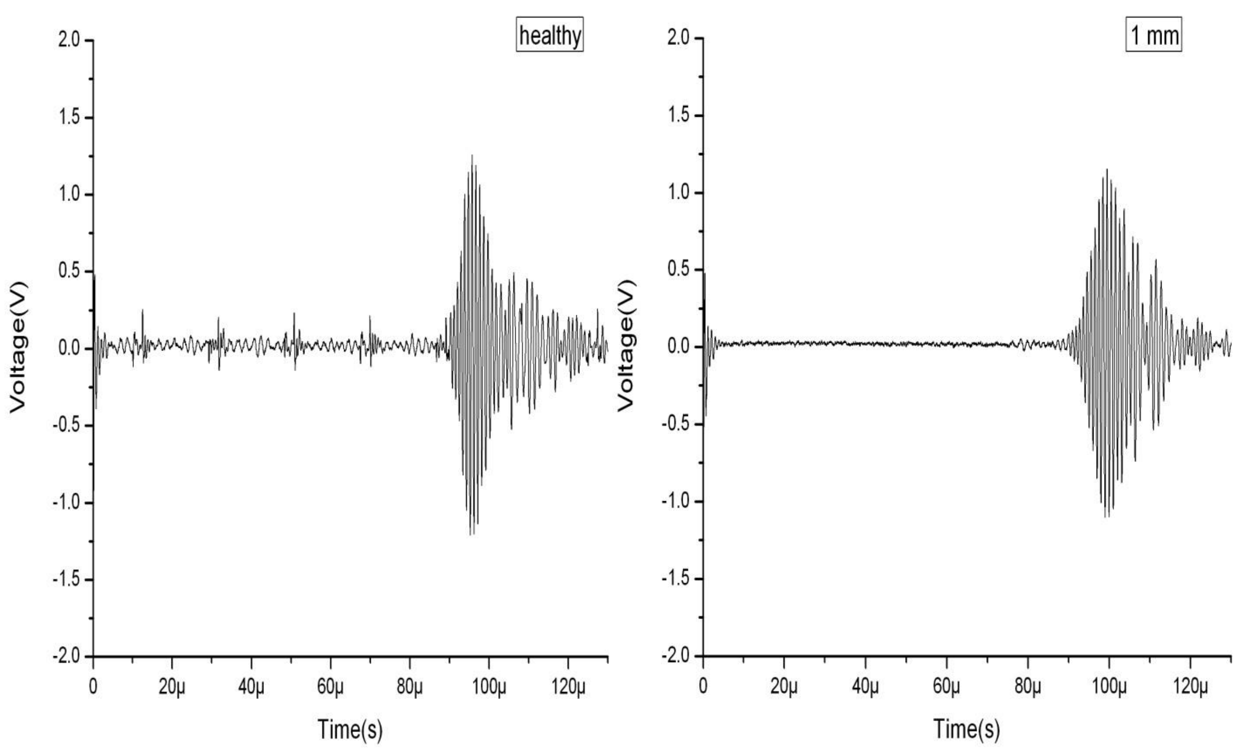
This indicates that L (0, 7) mode at 0.5MHz is sensitive to presence of notches in circumferential direction. It can be effectively used to detecting mass loss in pipes.

5.2.2 L(0,13) and L(0,12) mode at 1 MHz

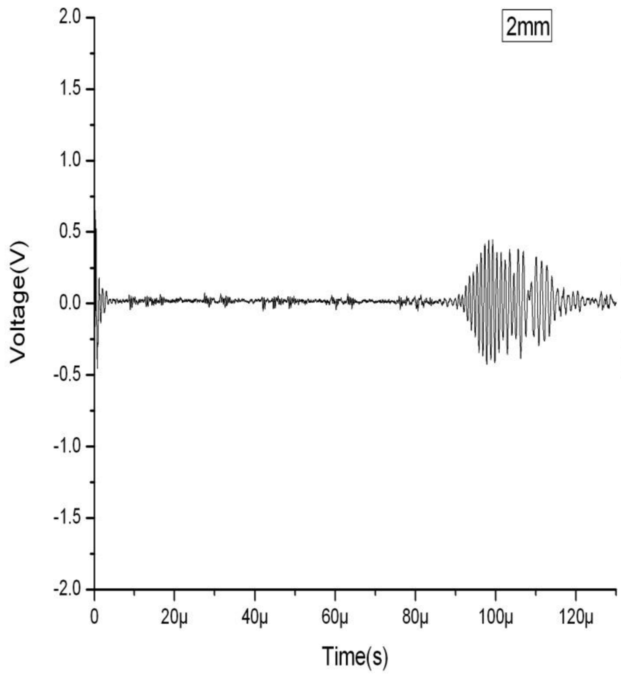
Similarly, pulse transmission investigations are further recorded on the same pipe using L (0, 12) and L(0,13) mode at 1MHz. Maximum gain for L(0,13) mode 56db and for L(0, 12) mode 54db has been used. Other settings remain the same to avoid any biases in the experiment.

L(0,13) mode at 1 MHz

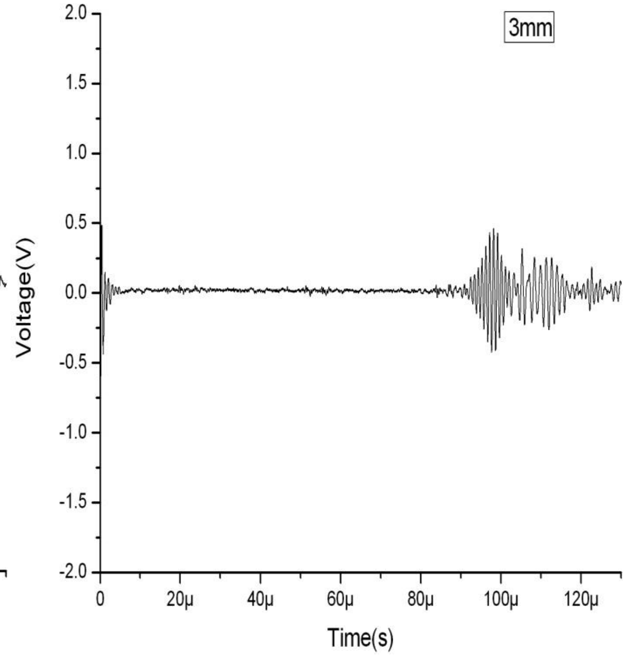
PT signatures obtained with L(0,13)mode are shown in **Figure 5.7**



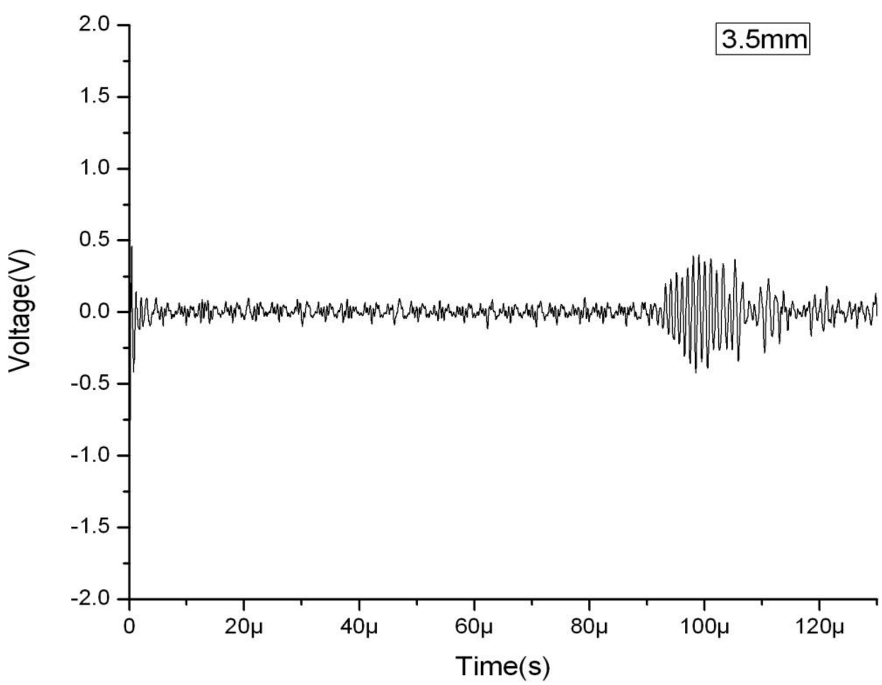
(a) (b)



(c)



(d)



(e)

Figure 5.7: PT signatures of L (0, 13) mode with 1MHz frequency for (a) healthy pipe (b)notch depth 1mm (c) notch depth 2mm (d) notch depth 3mm (e) notch depth 3.5mm

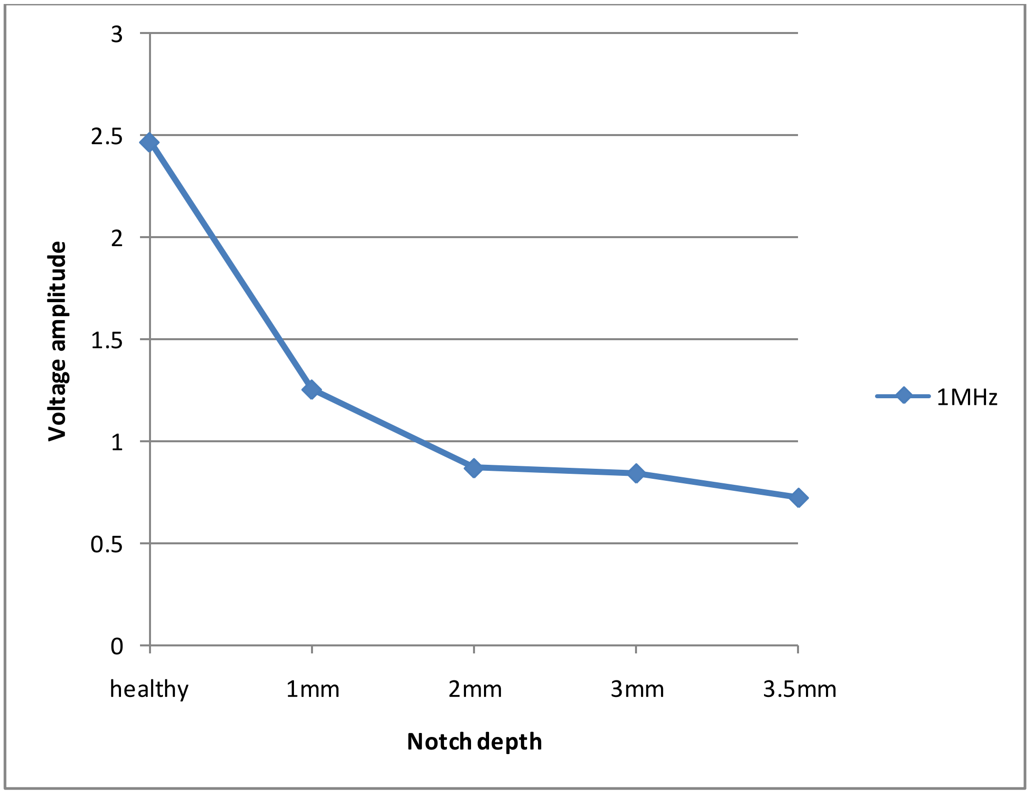


Figure 5.8: Peak to peak voltage with L(0,13) mode at 1MHz

It is observed from pulse transmission signals that as the depth of notch increases there is drop in signal amplitude (**Figure 5.7 and 5.8**) as in case of L(0,7) mode at 0.5MHz. But there is a marked difference in the two graphs. L(0,7) shows consistent drop in signal with increasing depth of notch but it is not true with L(0,13) mode.

There is a sharp decline in voltage amplitude up to 1mm depth of notch. Almost 50% of the voltage drop has been observed. But after 1mm of depth the signal is relatively stable and drop noted is very less. Further with increasing notch depth, the rate of fall of signal is found to be very sluggish. So, this shows that the L(0,13) mode is more effective in detecting the early damages but may not work effectively throughout.

Another significant observation is the scattering of the signal obtained with increasing notch depths and reduction in signal fidelity with L(0,13) mode in stark comparison to L(0,7) mode .

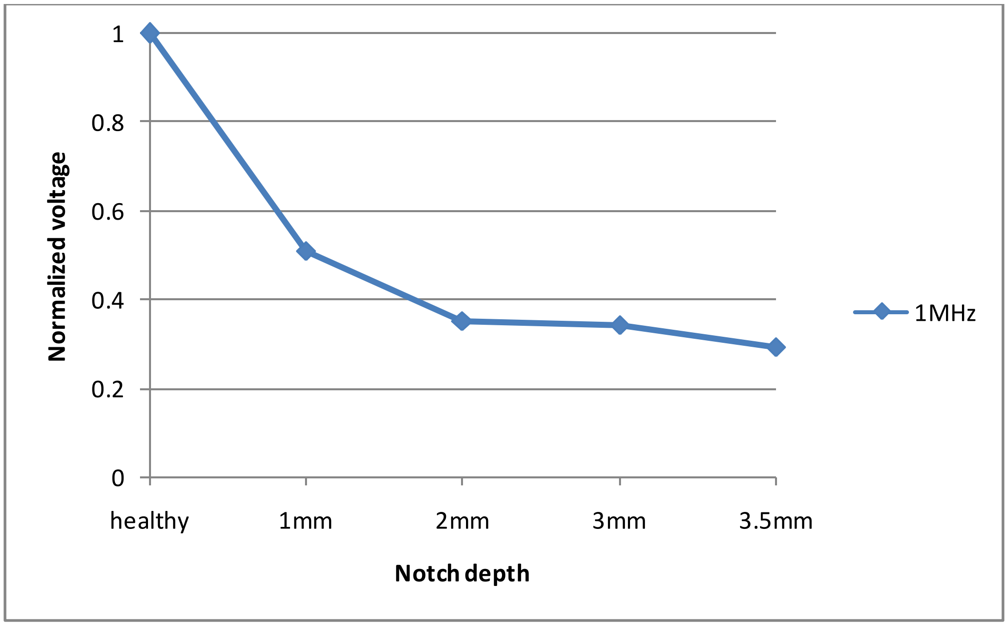
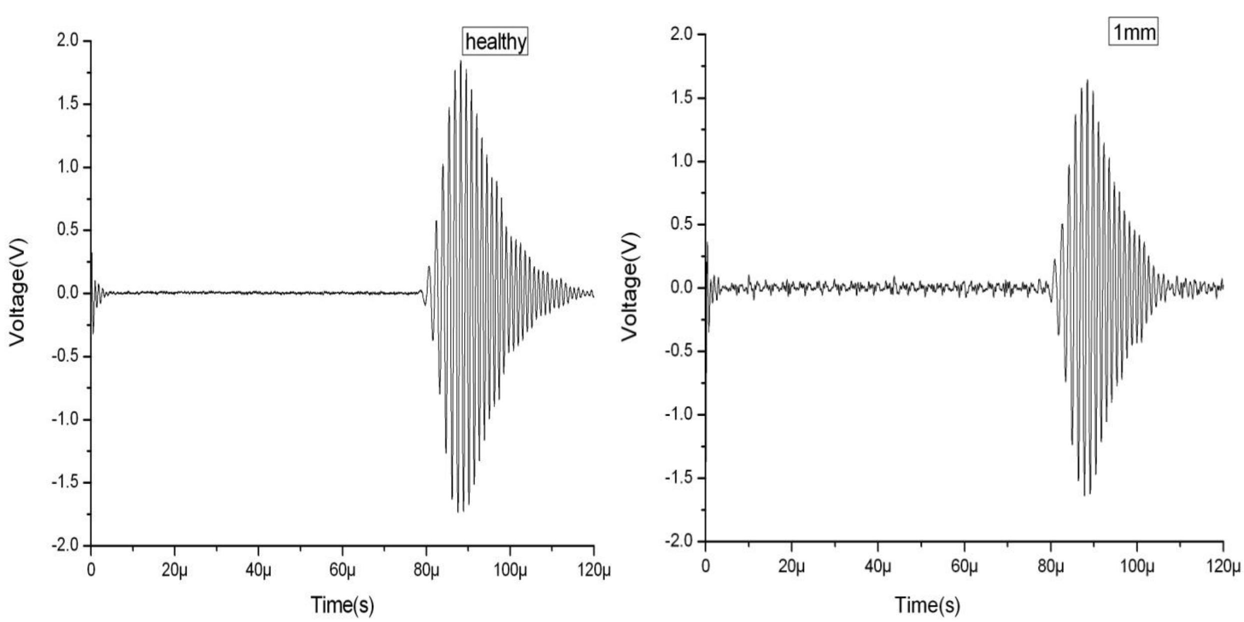


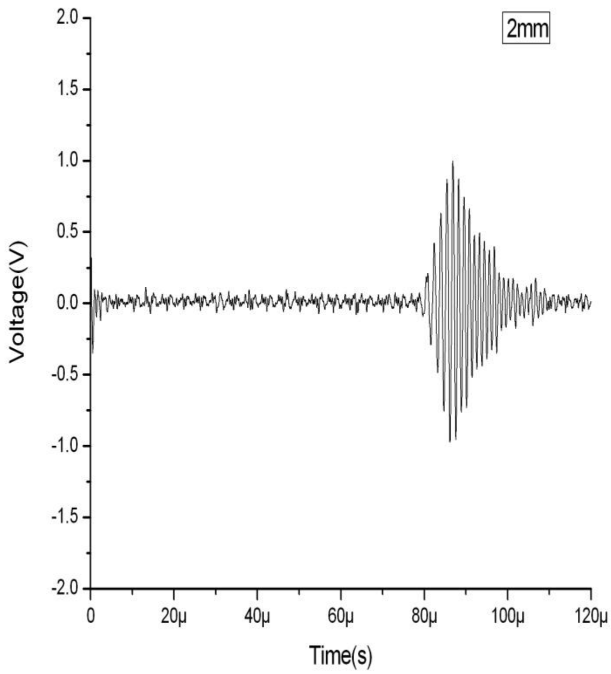
Figure 5.9: Variation in normalized voltage with increasing notch depth with L(0,13) mode

L (0, 12) mode at 1 MHz

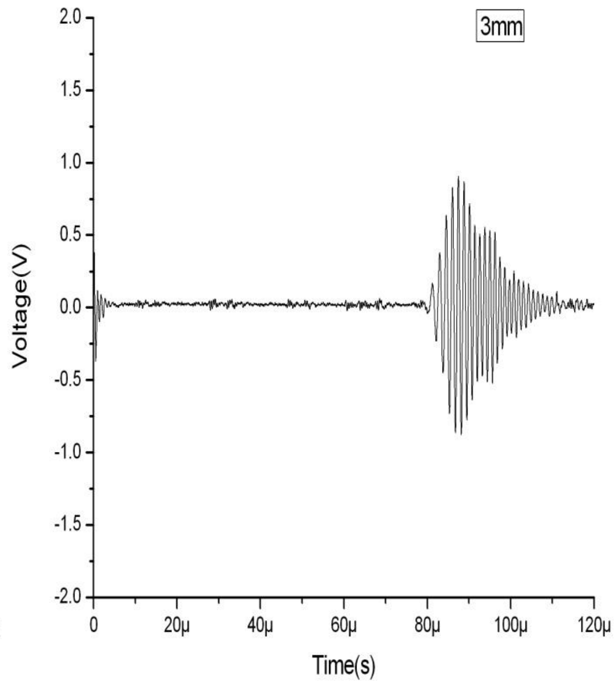
PT signatures using L (0, 12) with 1MHz frequency have also been recorded for healthy as well as specimen having notch defect of increasing magnitude. PT signatures are presented in **Figure 5.10**



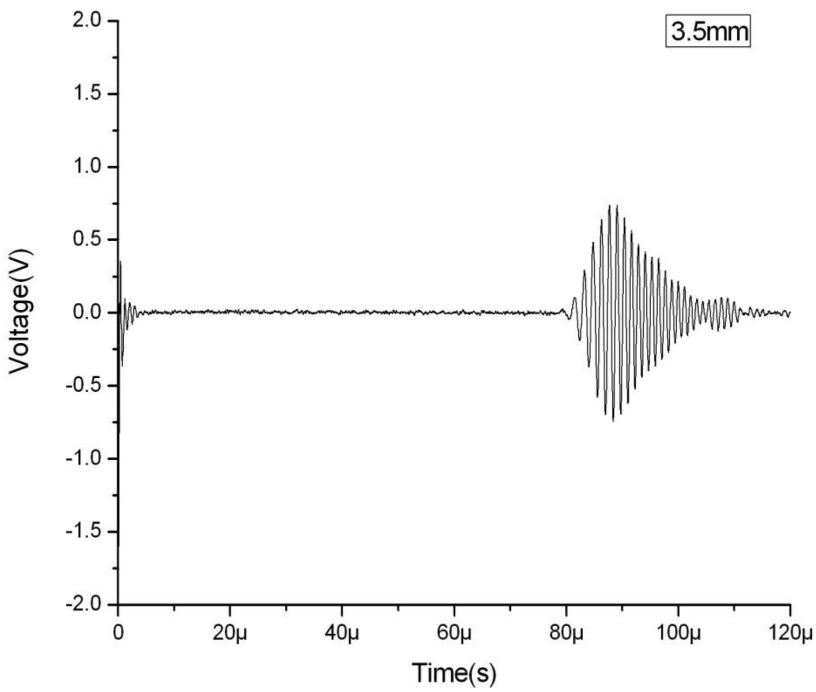
(a) (b)



(c)



(d)



(e)

Figure 5.10: PT signatures with 1MHz at different notch depth for (a) healthy pipe (b)notch depth 1mm (c) notch depth 2mm (d) notch depth 3mm (e) notch depth 3.5mm

Trends of fall with L (0, 12) mode are shown in **Figure 5.11.**

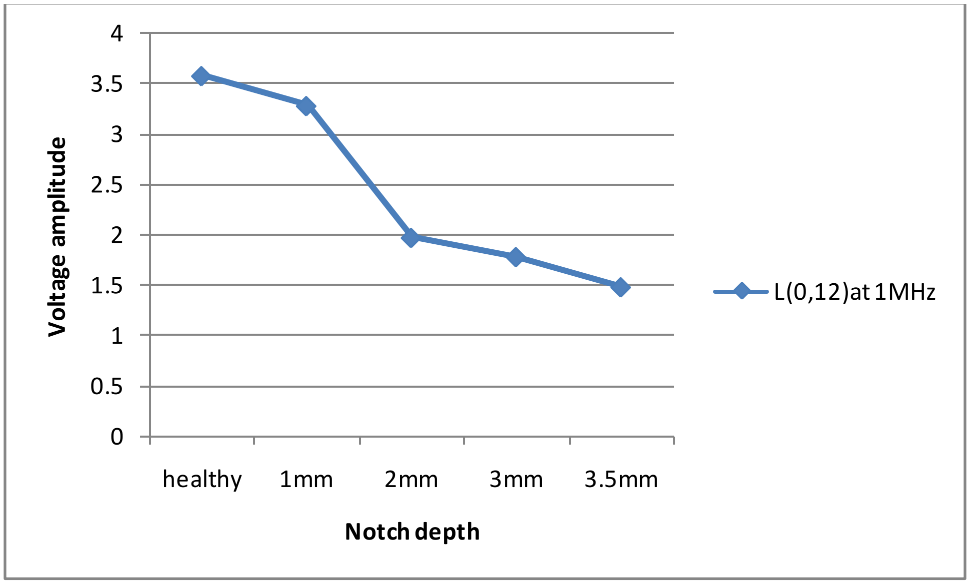


Figure 5.11: Peak to peak voltage of varying notch depth with 1 MHz

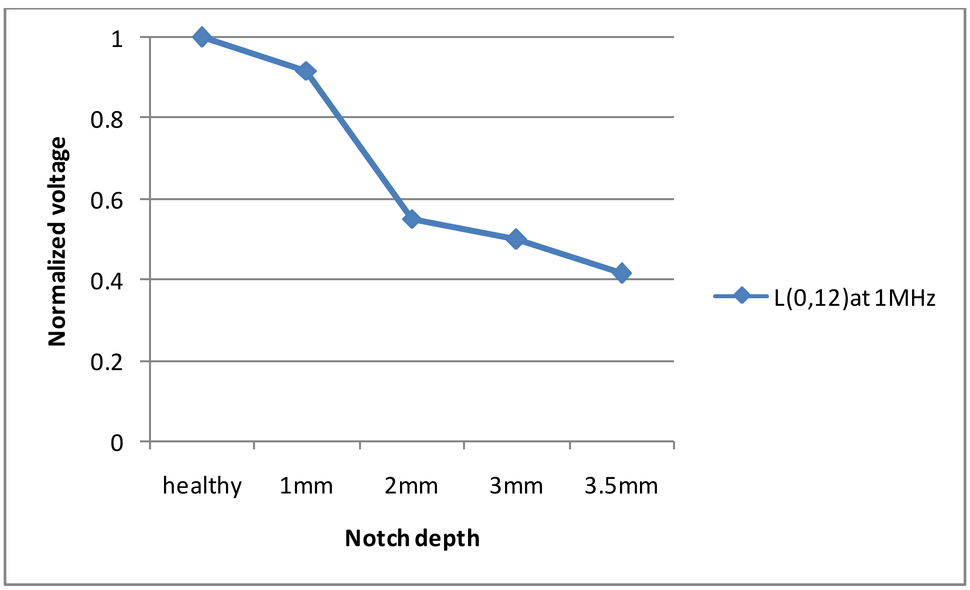


Figure 5.12: Normalized voltage with increasing notch depth

There is a visible drop in signal with increase in depth of the notch. Sharp voltage drop has been observed up to 2mm depth of notch. Normalized values also indicate **(Figure 5.12)** that up to 50% decrease in voltage amplitude has been noted when the depth of notch is 2mm deep as compared with healthy signal of the pipe. Further increase in depth of the notch marginal drop is observed.

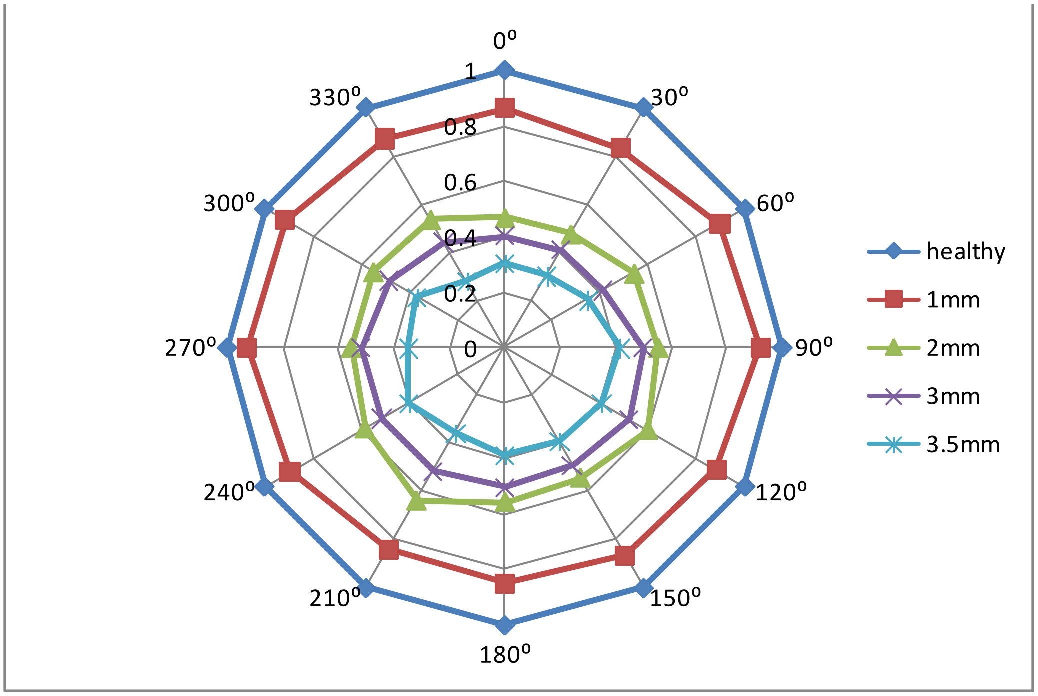


Figure 5.13: Circumferential normalized peak to peak voltage values at different notch depth with L(0,12) mode (1MHz)

The notch was all around the circumference of the pipe. Hence, the signals were also taken at all the location with increasing notch depth. Drop in voltage around the circumference is shown in **Figure 5.13.** It is observed that at all locations, drop in voltage amplitude is consistent and identical.

But an important observation is that the rate of fall of signal with increasing damage is not significant enough to be justified for use of this mode for damage detection in comparison to L(0,7) mode.

5.3 SUMMARY: SIMULATED NOTCH DAMAGES

From the pulse transmission investigations on pipes with notches, it has been observed that peak to peak voltage amplitude of the transmitted pulse decreases with increase in the depth of notch as compared with healthy signal. From the ultrasonic PT signatures, following key observation are made:

- There is a drop in voltage amplitude of the transmitted pulse with the increase in the depth of notch with all the three modes at selected frequencies. It indicates the presence of notch in pipe.
- At 0.5 MHz frequency with L (0, 7) mode, decrease in voltage is consistent and regular as the depth of notch increases.
- At frequency of 1MHz, signatures were recorded using both available L (0, 13) and L (0, 12) modes. Both the modes show drop in voltage as the depth of notch increases.
- For L (0, 13) mode quick fall in voltage is observed upto1mm depth of the notch at initial stage and poor drop afterwards as shown in **Figure 5.8, 5.9** is noticed. Also signal is sluggish as compared to other modes. This shows that the L(0,13) mode is more effective in detecting the early damages but may not work effectively throughout.
- Also the ultrasonic signal obtained for L (0, 13) mode is relatively not as clear and sharp when compared to other mode L (0, 7).
- With L(0,12) mode at 1 MHz, there is a visible drop in signal with increase in depth of the notch. Sharp voltage drop has been observed up to 2mm depth of notch. But with further increase in depth of the notch, marginal drop is observed. This mode may also not work as efficiently as L(0,7) mode for detecting notches in pipes because of sluggish behavior at larger depths of the notches.
- From the results, it is observed that notch is detectable with all the modes at selected frequencies. But L (0, 7) mode at 0.5 MHz shows a consistent and clear pattern of drop with increasing notch in comparison to other modes.
- This can be explained from the dispersive behavior of the modes at higher frequencies. At high frequencies (1 MHz in comparison to 0.5 MHz), multiple modes are generated resulting in scattering and attenuation of the signals. At low frequency of 0.5 MHz, only one mode is available L(0,7) hence giving clear signals.
- Hence, L(0,7) mode will be further used for detection of other damages in pipe i.e. hole and induced corrosion in pipes.

- Signatures were also taken around all around the circumference of the pipe with all modes as shown in **Figures 5.6, 5.13**.All the modes show consistent drop in voltage amplitude at each location with increase in notch depth. Hence, this technique can be effectively developed for damage detection in pipes.

5.4 SIMULATED HOLE DAMAGE IN PIPE

Circumferential hole is induced in the center of the pipe to study the surface defects in cylindrical pipes. Ultrasonic guided waves are used to detect the circumferential hole defect. Holes are formed on the surface generally due to casting defects, forging defects and corrosion. So there is need to study the presence of hole in a pipe for safety reasons.

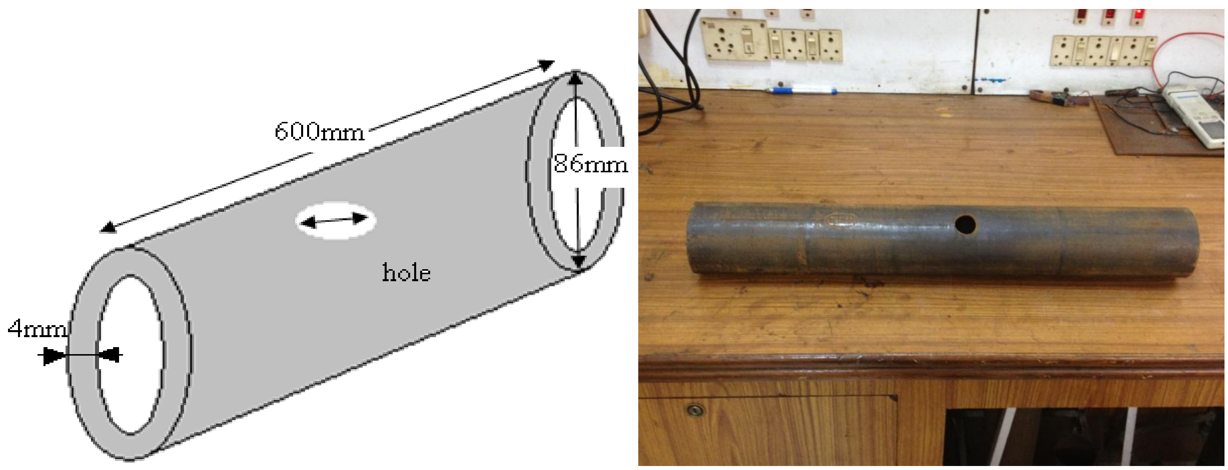
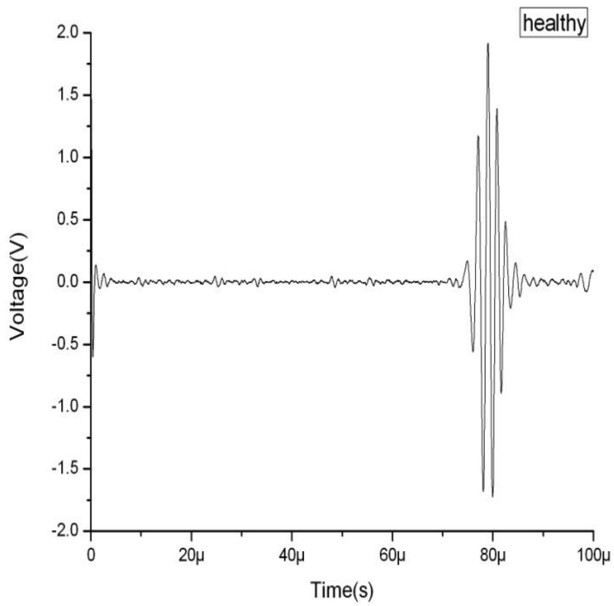
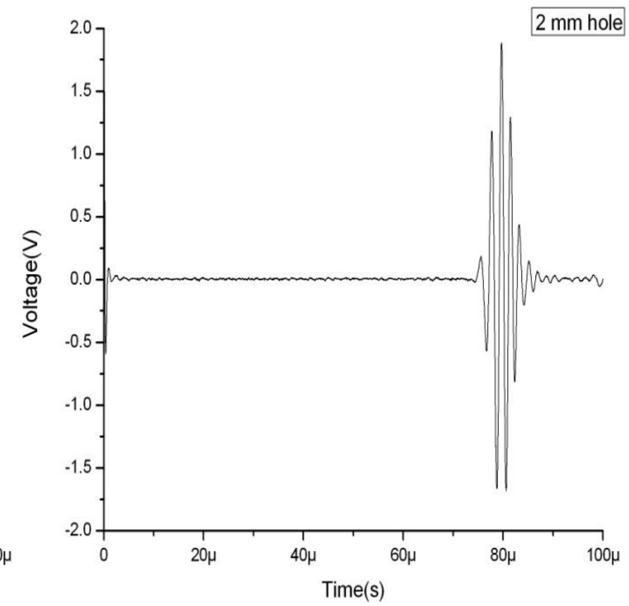


Figure 5.14: Specimen detail

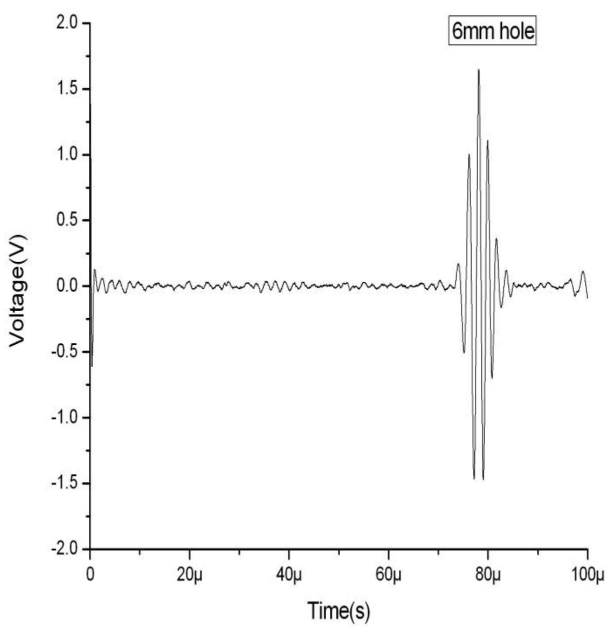
Hole is induced in the pipe with the help of drilling machine. At each step by increasing diameter size PT signatures have been recorded. Through transmission method is used to detect the hole in the immersed pipe. Scanning distance is same as of notch that is 200mm, with water path 40µs. Effect of hole at other location of pipe has also been studied by rotating the pipe from 0° to 360°. First healthy ultrasonic signal on different location are obtained, then after making through hole with increasing diameter size signatures have been recorded. The amount of damage has been compared with the healthy signal in the form of peak to peak voltage. PT signatures for L (0, 7) mode with 0.5MHz frequency are as under


healthy
Voltage(V)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
20μ
40μ
60μ
80μ
100μ
Time(s)

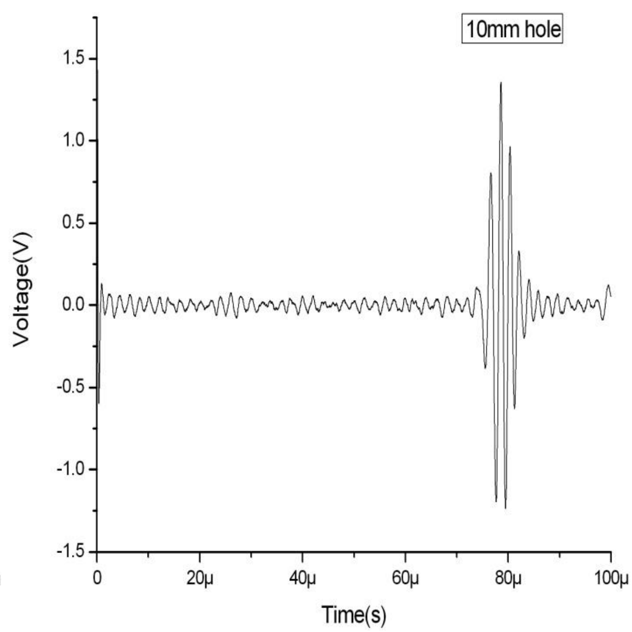
(a)


2 mm hole
Voltage(V)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
20μ
40μ
60μ
80μ
100μ
Time(s)

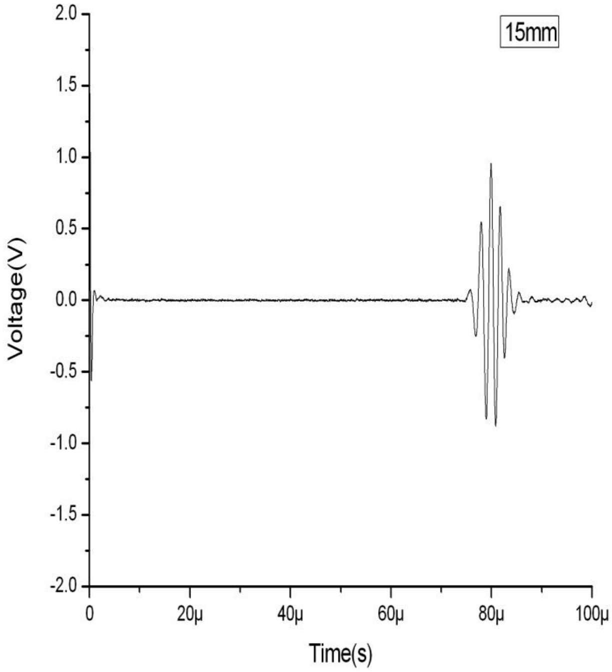
(b)

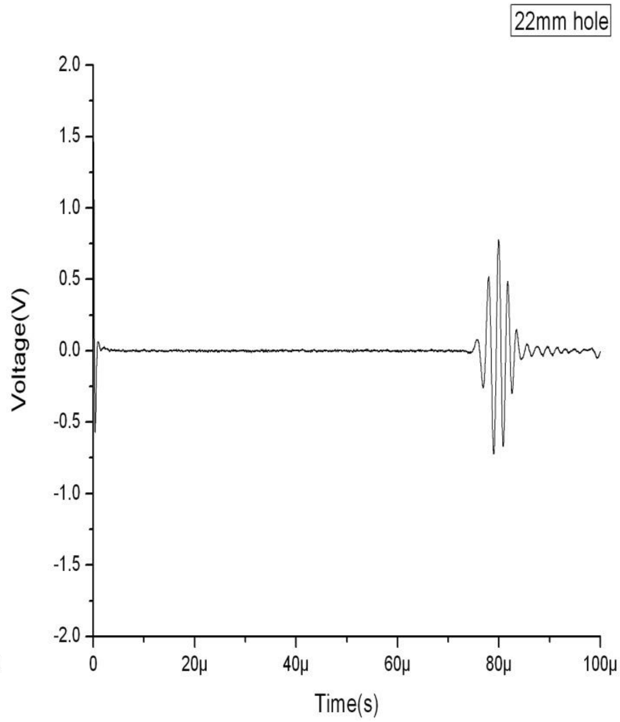

6mm hole
Voltage(V)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
20μ
40μ
60μ
80μ
100μ
Time(s)

(c)

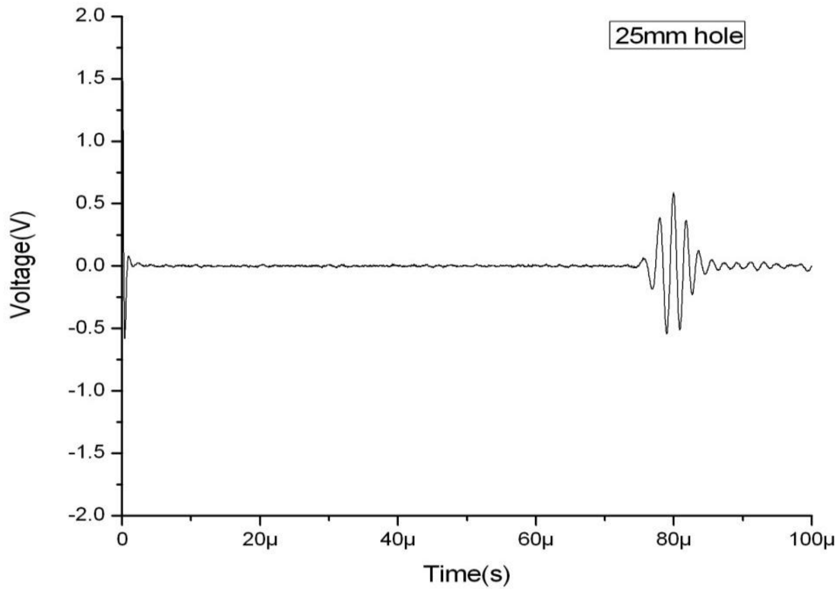

10mm hole
Voltage(V)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0
20μ
40μ
60μ
80μ
100μ
Time(s)

(d)





(e) (f)



(g)

Figure 5.15: PT signatures with L(0,7) mode at 0.5MHz with (a) healthy (b) 2mm hole (c) 6mm hole (d) 10mm hole (e) 15mm hole (f) 22mm hole (g) 25mm hole

From the **Figure 5.15** drop in voltage amplitude with increase in diameter size has been observed. The drop in voltage amplitude shows the presence of hole and with L (0, 7) mode at 0.5MHz frequency it is detectable.

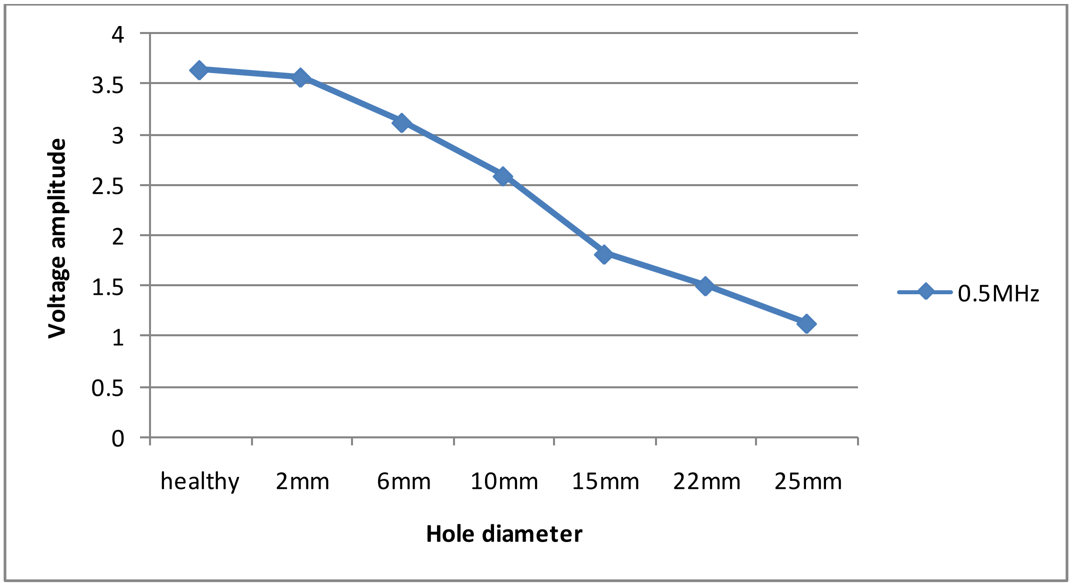


Figure 5.16: Peak to peak voltage with L(0,7) mode by increasing hole diameter

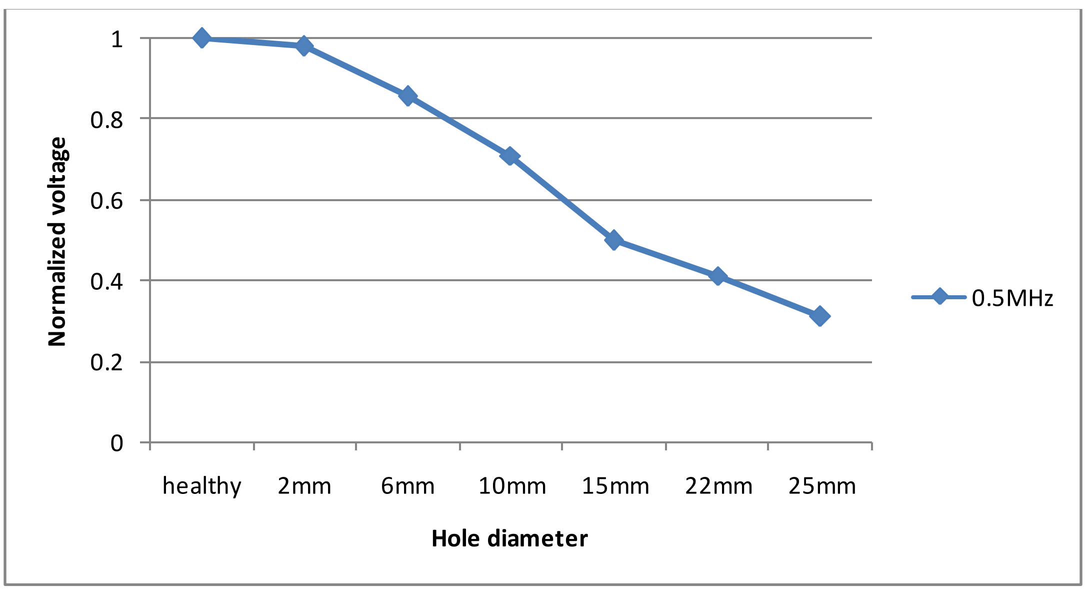


Figure 5.17: Normalized peak to peak voltages at different diameter with L(0,7) mode

From the ultrasonic signal normalized value of voltage amplitude is obtained as shown in **Figure 5.17.** There is drop in voltage amplitude as the diameter of hole increases. When there is 2mm hole the decrease in voltage is very slight but later than it is almost regular and constant. Up to 70% of decrease in voltage has been noted. The main reason of drop in voltage amplitude after 10mm hole diameter is the size of transducers. The diameter of transducers are 25mm and ultrasonic waves spreads only on this area so when the hole diameter increases more waves are consumed and drop in voltage amplitude is observed.

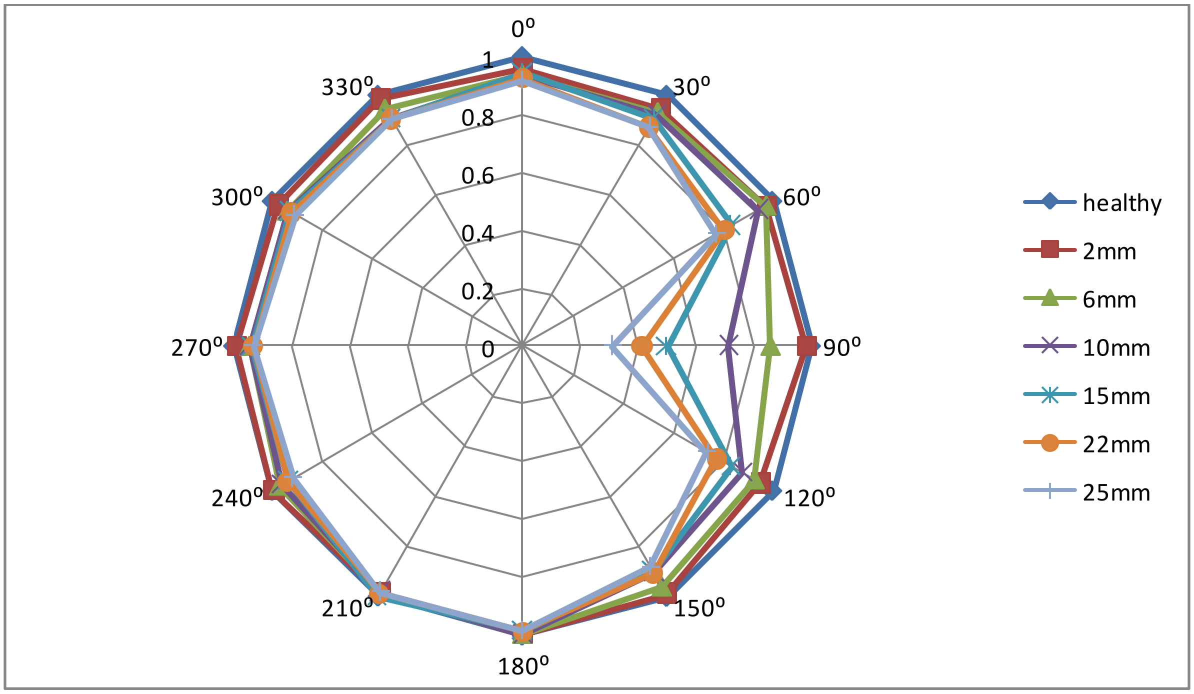


Figure 5.18: Voltage amplitude at different location of the pipe with L(0,7) mode

Voltage amplitude by increasing diameter size with L (0, 7) mode at different locations has been shown in **Figure 5.18.** It is figured out that maximum drop in voltage occurs at the location of the hole which is marked as 90°. On the other locations no drop has been seen. But when the hole size is increased further the decrease in signal at corresponding location (60° and 120°) has been observed. Hence the reduction of the material in pipe has been detected which is related with drop in voltage.

5.5 SUMMARY

From the ultrasonic signatures obtained from testing of pipe at L (0, 7) mode with 0.5MHz frequency by increasing diameter size following observations are made

- Decrease in peak to peak voltage indicates the presence of hole when compared with the healthy signal because due the presence of hole waves are consumed and shows drop in amplitude voltage.
- Voltage amplitude keep on decreasing as diameter of the hole increases. As hole diameter increases less energy reaches to the receiving probe shows drop in voltage amplitude.
- Signatures are obtained circumferentially around the pipe and maximum voltage drop occurs at 90^0 location because presence of hole. Negligible drop in voltage at other location has been seen. But at position of hole at 90^o shown in **Figure 5.18** has consistent decrease in voltage.
- The drop in voltage amplitude at 60^o and 120^o locations has been observed after 10mm of diameter size. This is because transducers are of 25mm diameter and waves spreads only in this area so when diameter of hole increases, waves consumption increases shows drop in voltage amplitude.

Hence it is observed that with 0.5MHz frequency using L (0, 7) mode defect like hole in pipe is detectable and this mode is good in characterizing the damages in pipes.

CHAPTER 6

DAMAGE DEFECT –CORROSION

6.1 GENERAL

In the previous chapter ultrasonic guided waves have been used to identify the presence and extent of simulated defects like notches and hole in pipes. This chapter deals with the detection of corrosion damage in pipes.

Corrosion is the deterioration of materials by chemical action of some surroundings or contacting medium, which may be liquid, gas or combination of two. Corrosion can influence all metals, but the effect varies widely depending upon combination of the metal and the corrosive agent. So corrosion can cause serious damage to pipes that is why it is important concern for study.

There are millions of kilometers of pipelines throughout the world. Many of these pipelines carry hazardous liquids such as nuclear reactor coolant or petrochemical. The environmental and economic ramifications of any leakage of these substances are often very severe. Therefore, a clear need for defect detection exists to avoid the risk of failure and its consequences. Subsequently, the system has been employed where external access to the pipe is limited, such as road crossings where the pipe is buried, or offshore risers where the some of the pipe is submerged in water. Due to the presence of fluids and liquids in pipes they are more prone to corrosion.

Corrosive environments that cause corrosion can produce failure in two ways. The corrosion may actually reduce the amount of material and most important it can produce pits and holes in the pipes. Corrosion in pipes mainly occurs due to direct environmental attack like exposure to moisture, air and acidic solution. Sometimes it is not possible to inspect the corrosion visually like in buried pipes, inside the boilers and under water pipe lines etc. So there is need to use NDT techniques to study the corrosion rate.

In this study detection of corrosion in pipes has been studied using ultrasonic guided waves. Methodology developed in previous chapter has been applied to submerged pipes suffering material loss in the form of corrosion.

6.2 CORROSION STUDIES

6.2.1 Mechanism of corrosion

Corrosion is destructive phenomenon and in some cases cause material failure. Corrosion is the process of metal wastage produced by chemical action (oxidation). Natural corrosion takes long time hence accelerated corrosion has been used to corrode the mild steel pipe. Commonly used methods of accelerated corrosion are

1) Electrolysis corrosion/Impressed current corrosion method

2) Dipping in acidic solution

3) Salt mist chamber

4) Alternate drying and wetting

From the above mentioned techniques, impressed current technique has been used because it is the fastest and quickest way of producing corrosion. In impressed current corrosion two dissimilar metals are kept in an electrolyte and also having external electrical contact with each other. At least one of the metals must have a positive oxidation potential. A potential difference due to the different oxidation potentials of the metals causes electrons to flow in the circuit. Oxidation (corrosion) occurs at the anode where metal is removed. Reduction (of electrolyte) occurs at the cathode.

Following reactions occurred when the current is passed

When metal is placed in contact with liquid, surface ionization occurs because of electric charge difference at solid liquid interface. Iron dissolved in water in form of positively charged ferrous ion.

At the Anode:

$Fe \longrightarrow Fe^{2+} + 2e^-$ (current) ……………………………………… (6.1)

At the Cathode:

$2e^- + 2H^+ \longrightarrow H_2$ (bubbles) ………..………………………..…... (6.2)

Positively charged ferric ions are attracted to negatively charged hydroxyl ion and form the corrosion product.

In the Electrolyte:

$H_2O \rightleftharpoons OH^- + H^+$ .... (6.3)

$Fe^{2+} + 2OH^- \longrightarrow Fe(OH)_2$ (corrosion product) .... (6.4)

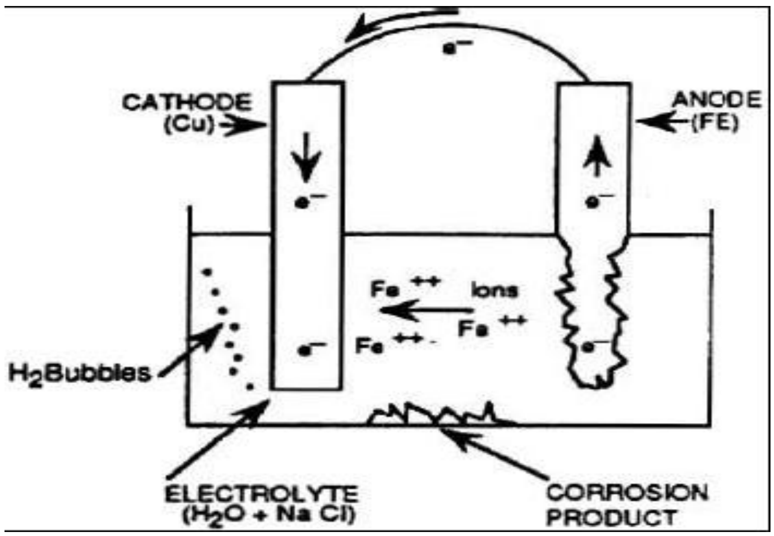


Figure 6.1: Mechanism of corrosion

This method has been used for the corrosion of the MS pipe. Set up has been made according to the area to be corroded. By this method corrosion rate can also be controlled by controlling the external current.

6.2.2 Experimental details

Mild steel hollow pipe has been used with dimensions 600mm long, 86mm external diameter and 4mm thickness. Weight of the healthy pipe (before corrosion) recorded as 2982gm. Impressed current corrosion has been done only for a localized area of 125mm length. An acrylic pond of dimension (125mm x 125mm x 150 mm) was constructed over the pipe for restricted exposure as shown in **Figure 6.2**. Tank was sealed by araldite to avoid any leakage of the electrolyte.

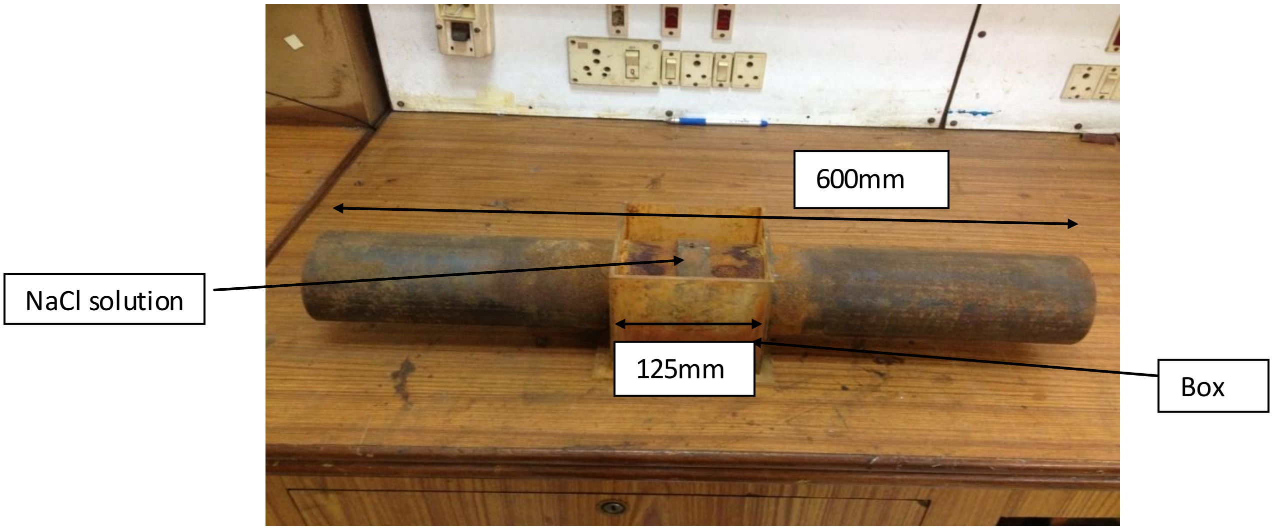
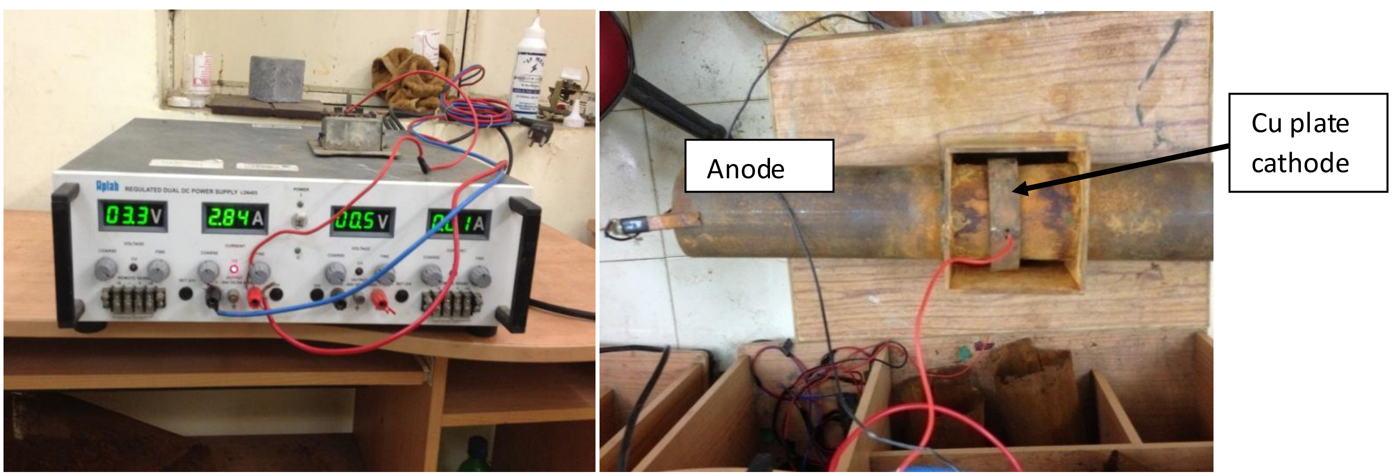


Figure 6.2: Detail for inducing corrosion

To induced impressed current corrosion, DC power supply of 34V capacity (Figure 6.3) Aplab make was used shown in **Figure 6.3(a).** It provides adjustable levels of current and voltage values. Variable resistance has been used in series to regulate the current in circuit. Connections were made by using copper wires and crocodile clips.



(a) **(b)**

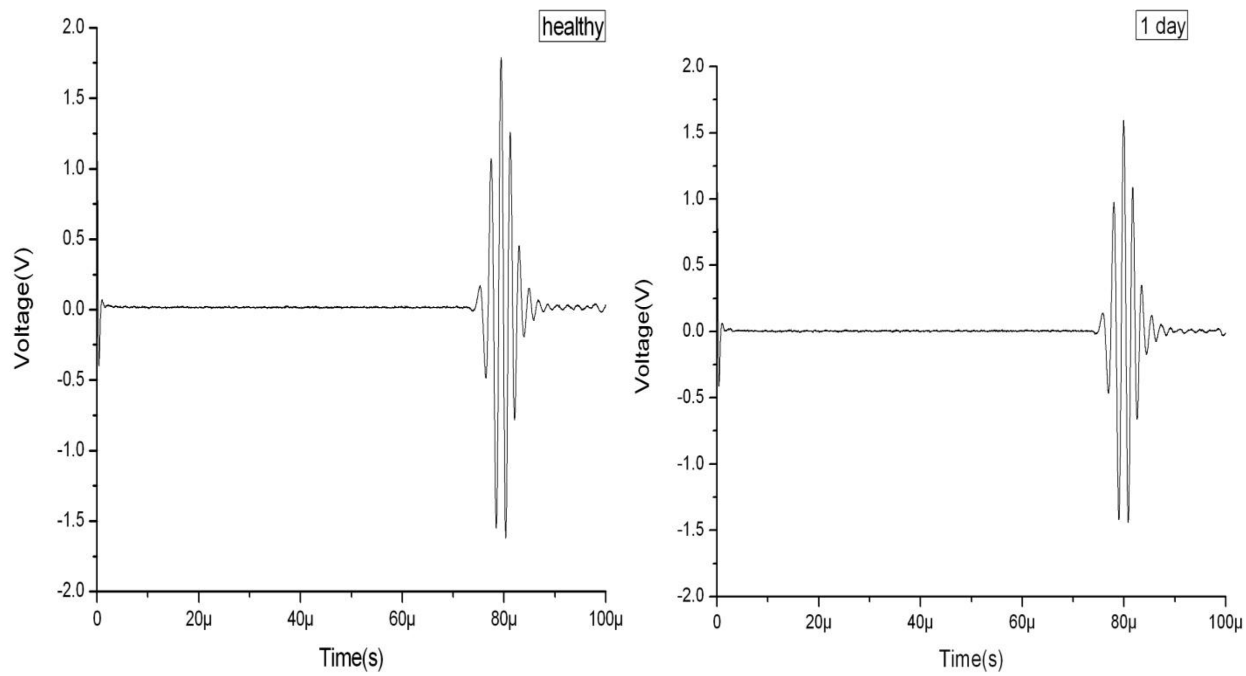
Figure 6.3: (a) Power supply unit (b) Pipe setup

Steel pipe was connected to the positive terminal to the power supply and serves as anode. An external cathode of copper strip (125mm x 30mm x 5mm) was used as cathode (**Figure 6.3 b**).

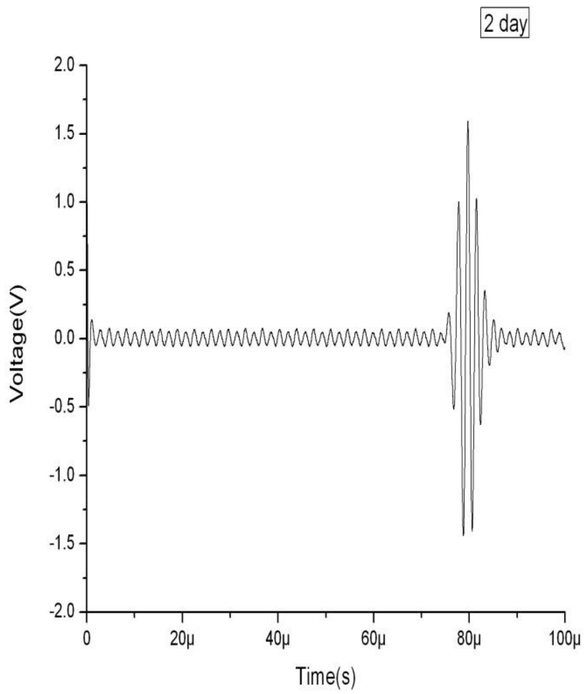
The cathode was immersed in acrylic tank fixed on pipe in 3.5% NaCl solution to provide chloride environment and induce faster corrosion. Copper plate is placed over the pipe in such way that it does not touch the pipe. Copper plate was placed flat over the pipe but corrosion was not satisfactory. Shape of copper plate has been modified and made according to the shape of pipe for effective corrosion.

6.3 ULTRASONC INVESTIGATIONS

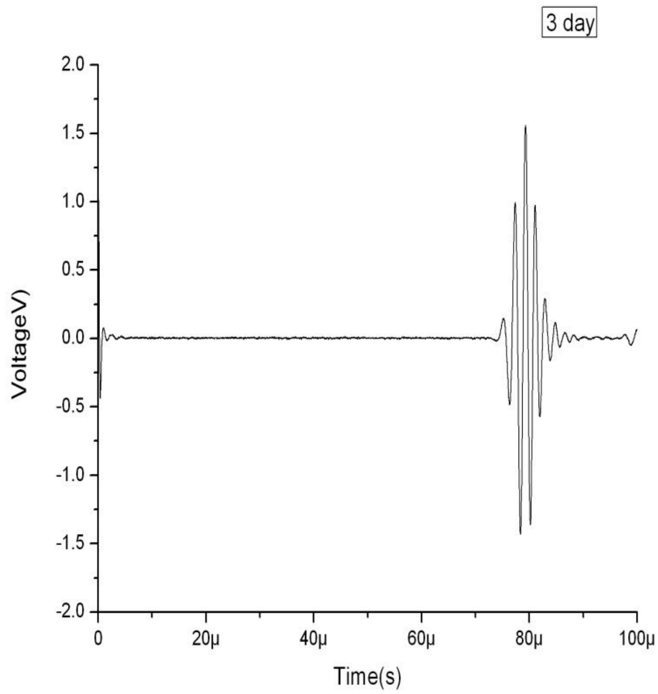
Pipe was marked from 0° to 360° with 30° gap for taking ultrasonic pulse transmission signatures at all the locations. Healthy PT signatures using the selected mode of L(0,7) at 0.5MHz were taken at all locations of the pipe. 34V and current of 0.40A was maintained for accelerated corrosion and was continued for 24 hours. Pond was dismantled and PT signatures were again taken at all locations after 24 hours of corrosion. Pond was reconstructed and corrosion continues till the corrosion gave way to holes in the pipe. This continued till ten days. **Figure 6.5** shows the PT signatures of L(0,7) mode at 0.5MHz after every 24 hours of corrosion. **Figure 6.5 and 6.6** shows the peak to peak voltage ratio trends for the signals at four locations.



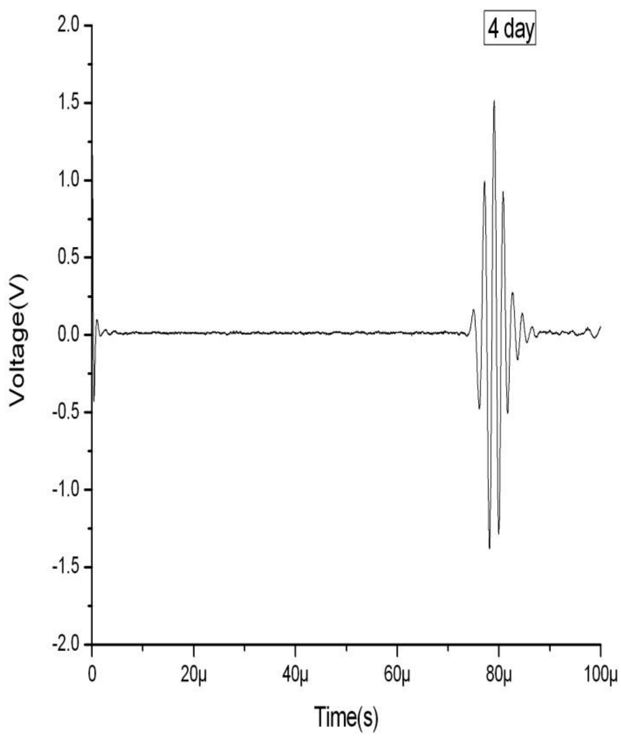
(a) (b)


2 day
Voltage(V)
Time(s)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
20µ
40µ
60µ
80µ
100µ

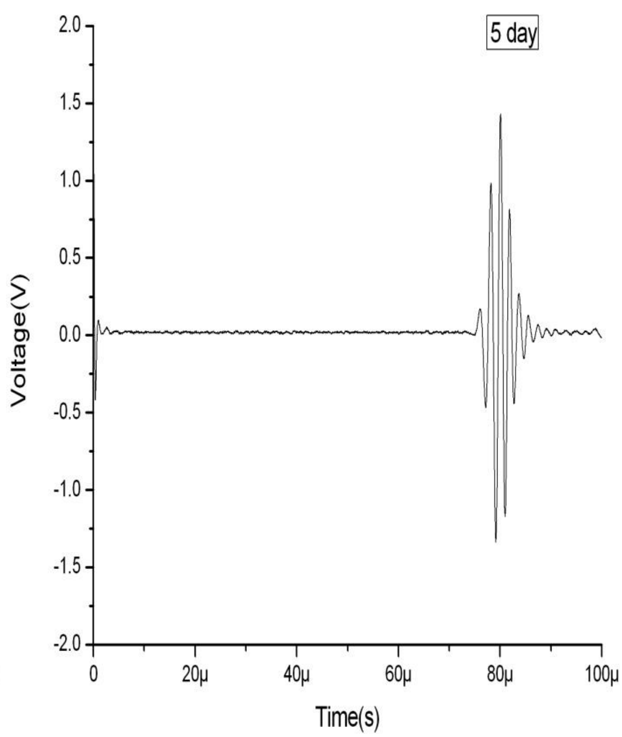
(c)


3 day
VoltageV)
Time(s)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
20µ
40µ
60µ
80µ
100µ

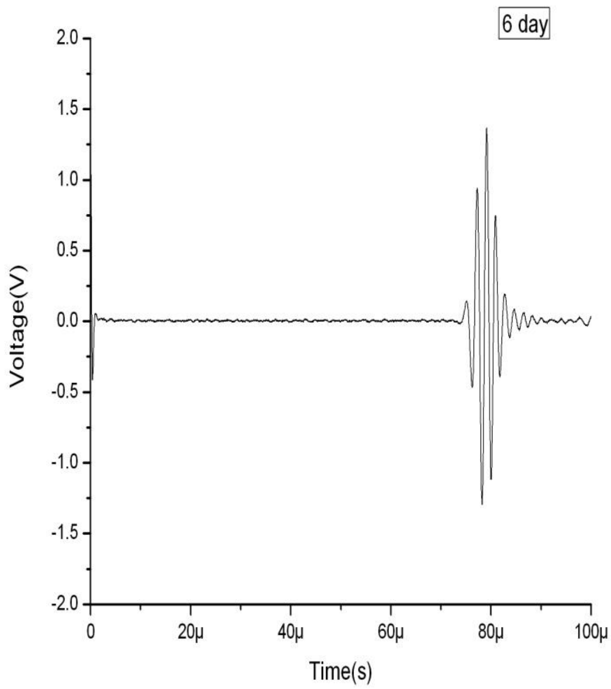
(d)


4 day
Voltage(V)
Time(s)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
20µ
40µ
60µ
80µ
100µ

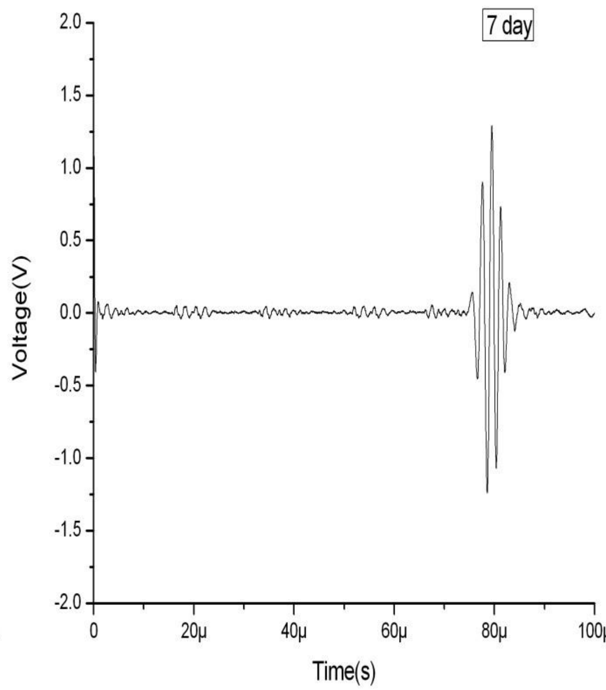
(e)


5 day
Voltage(V)
Time(s)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
20µ
40µ
60µ
80µ
100µ

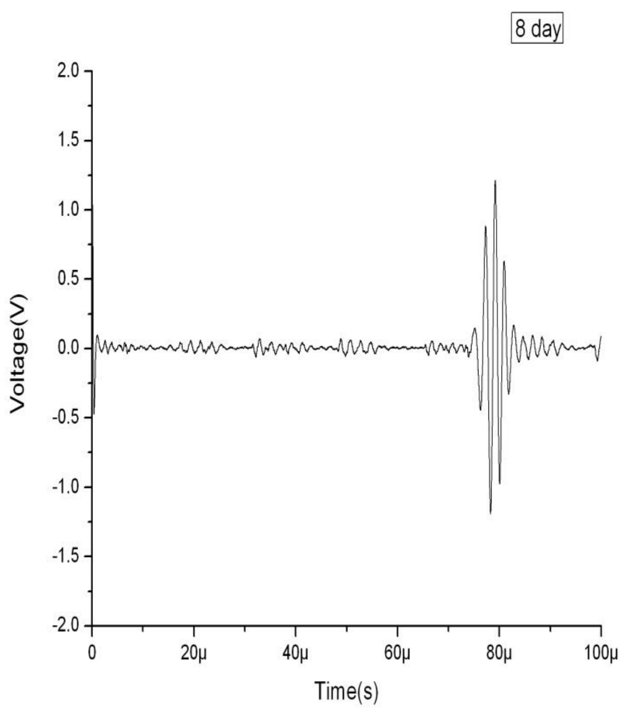
(f)


6 day
Voltage(V)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
20μ
40μ
60μ
80μ
100μ
Time(s)

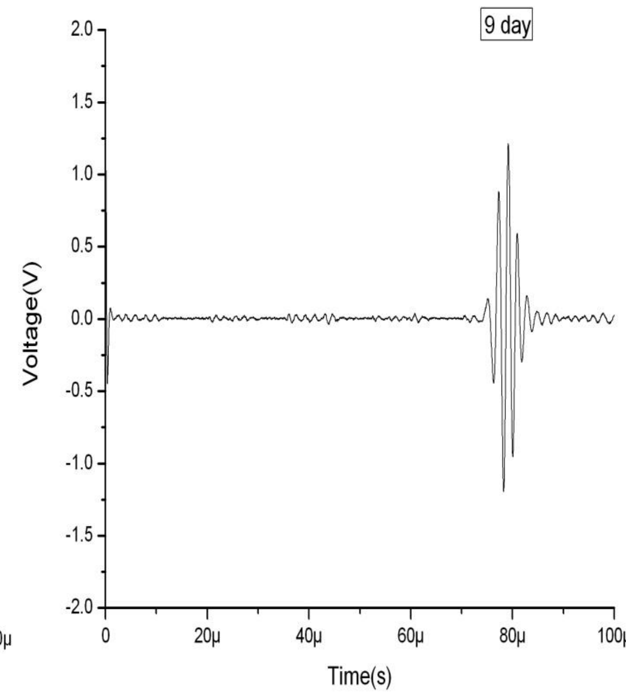
(g)


7 day
Voltage(V)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
20μ
40μ
60μ
80μ
100μ
Time(s)

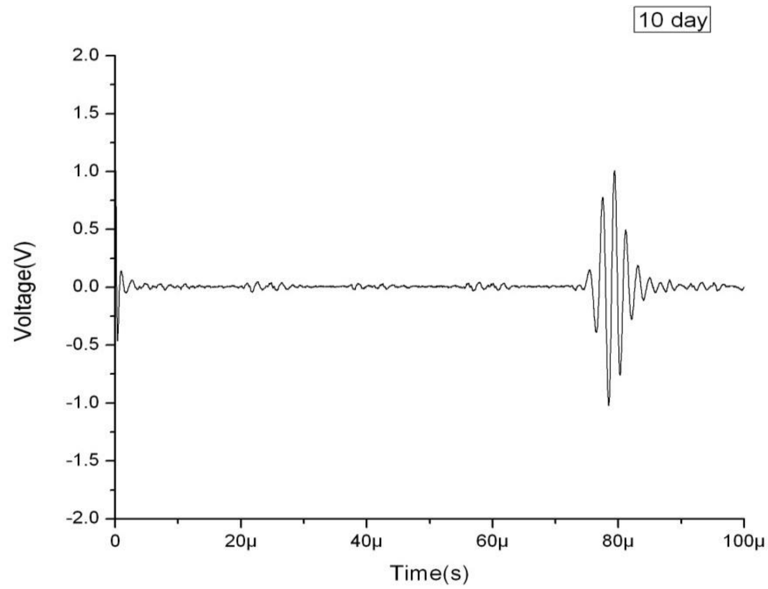
(h)


8 day
Voltage(V)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
20μ
40μ
60μ
80μ
100μ
Time(s)

(i)


9 day
Voltage(V)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0
20μ
40μ
60μ
80μ
100μ
Time(s)

(j)



(k)

Figure 6.4: PT signatures with L(0,7) mode at 0.5MHz with (a) healthy (b) 1 day of corrosion (c) 2 day of corrosion (d) 3 day of corrosion (e) 4 day of corrosion (f) 5 day of corrosion (g) 6 day of corrosion (h) 7 day of corrosion (i) 8 day of corrosion (j) 9 day of corrosion (k) 10 day of corrosion

From the PT it is observed that there is drop in signal with increasing exposure to corrosion. **Figure 6.5** shows the condition of the pipe after ten days of corrosion.

Figure 6.5: After corrosion hole formation in pipe

Figure 6.6 and Figure 6.7 shows the trends of voltage amplitude of PT signal taken with L(0,7) mode at 0.5MHz for four locations. There is drop in voltage amplitude as the number of corrosion days increases.

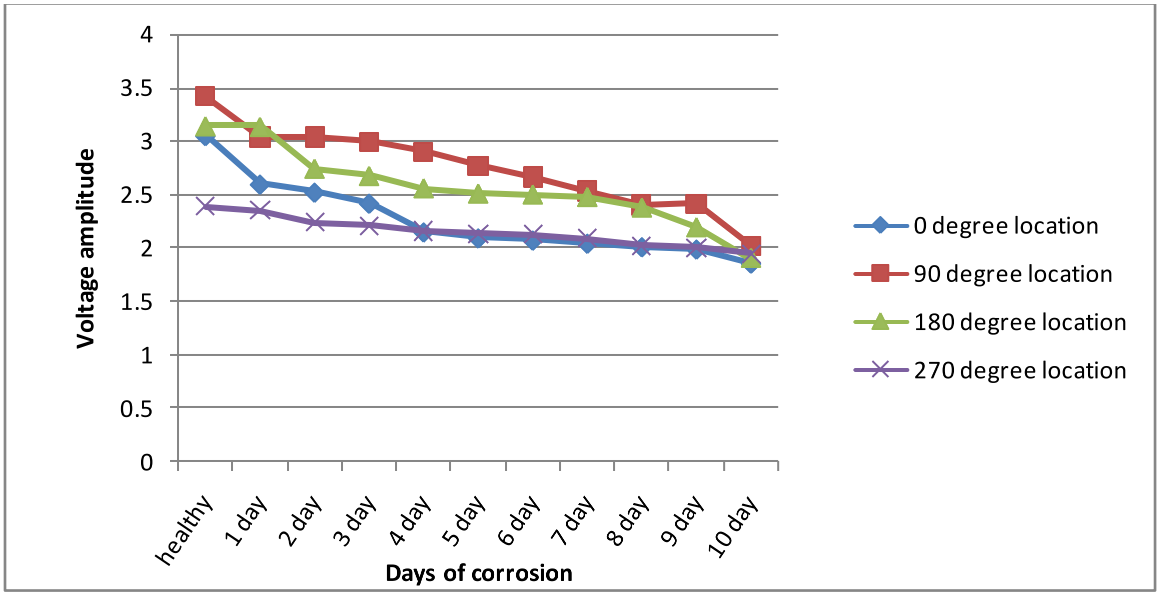


Figure 6.6: Peak to peak voltage trend with L(0,7) mode

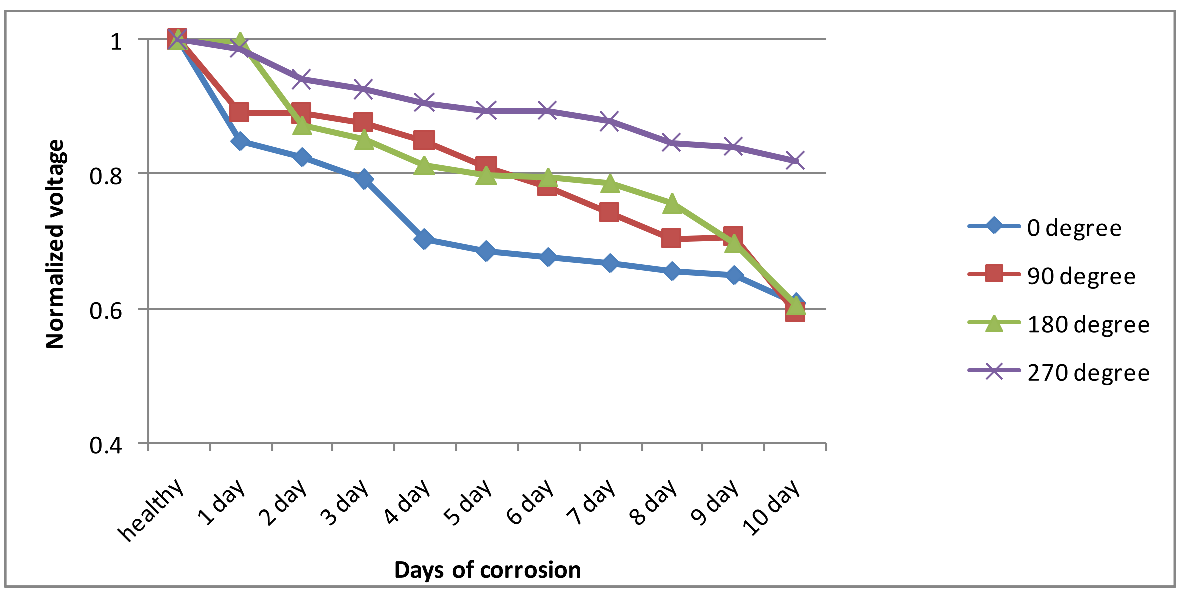


Figure 6.7: Normalized voltage with increasing days of corrosion exposure

Figure 6.8 shows the voltage amplitude taken at all locations in form of spider graph

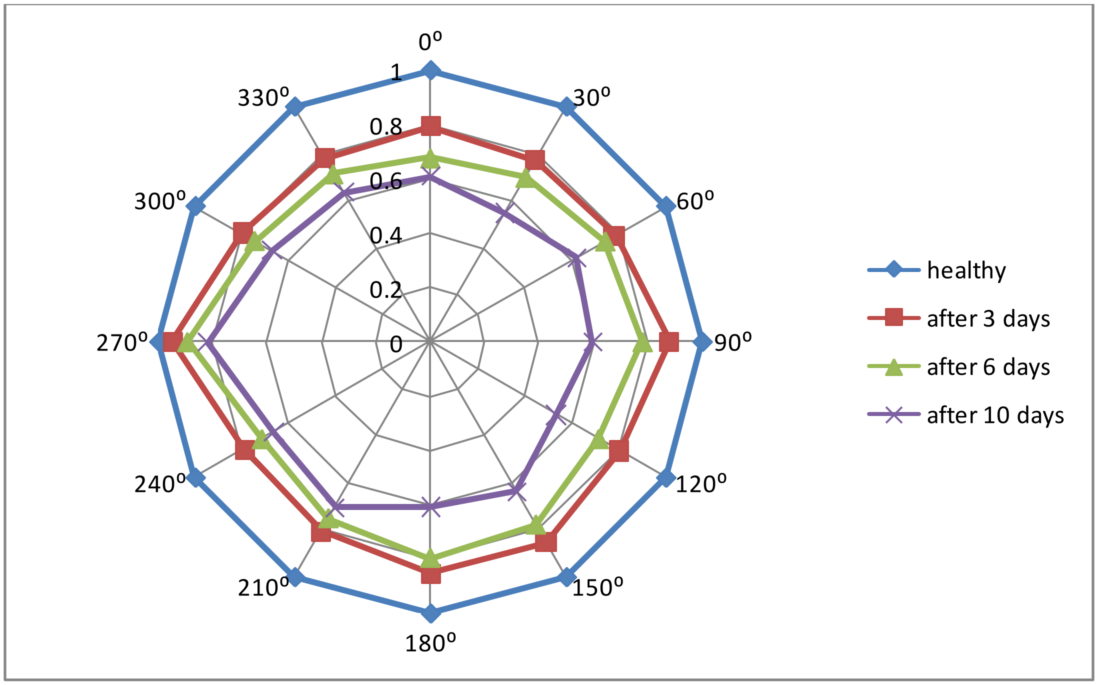


Figure 6.8: Voltage amplitude at different locations

Signatures at different location were taken and voltage amplitude at these locations has been shown in the **figure 6.7**.

From the ultrasonic signatures taken in pipe at 0.5 MHz frequency with L (0, 7) mode following observations are made

- There is fall in voltage amplitude with increase in corrosion exposure. The drop in peak to peak voltage is shown in **figure 6.5, 6.6.**
- The drop in voltage is due to corrosion of pipe resulting in mode scattering and attenuation of signal. Corrosion reduces the area of the pipe non-uniformly and eats the signal.
- In comparison to simulated machined notches, with clear area reduction, corrosion being non-uniform and widespread causes relatively less attenuation of signal.
- Corrosion spreads all around the pipe. Subsequently localization of mass loss in the form of pitting is not observed.
- Initially signal fall is sluggish but later the fall is consistent.

- Maximum drop in voltage is observed at 30°, 90° and 120° location. At 90° location the formation of hole is detected at end of corrosion **(Figure6.5).**
- Also drop in voltage amplitude is consistent at almost every location except 270°. This is because of pipe joint at that location.

Hence it is concluded that corrosion occurring in pipe can be picked up by specific ultrasonic guided wave. Attenuation of the PT signal can relates to the extent of corrosion.

6.4 CORRELATION BETWEEN ULTRASONIC VOLATGE AND MASS LOSS DUE TO CORROSION

With increasing corrosion exposure, loss of mass in pipe was also recorded. Figure 6.9 shows the plot of loss in mass due to corrosion with days of corrosion

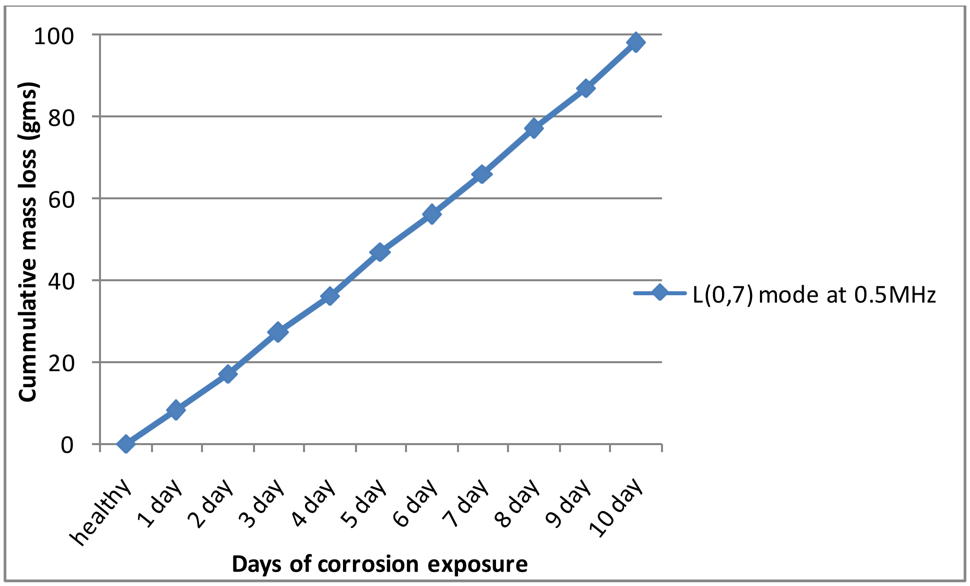


Figure 6.9: Mass loss v/s days of corrosion exposure

It is observed that with increasing exposure to corrosion environment, loss in mass increases. It shows regular and consistent drop in pipe mass as the number of days increases.

An attempt has been made to establish relation between ultrasonic voltage drop with increasing corrosion with loss in mass **(Figure 6.10).**

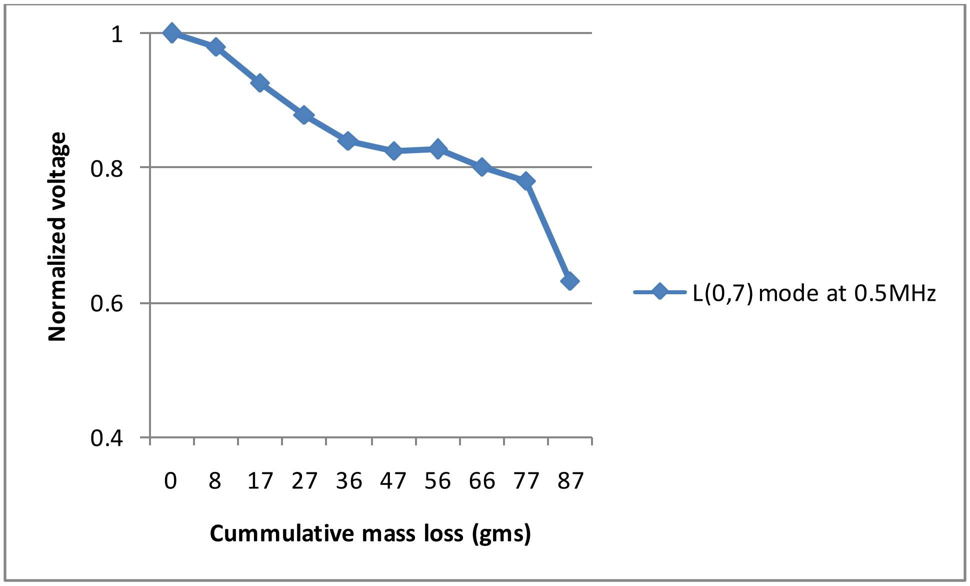


Figure 6.10: Peak to peak voltage drop with weight of pipe as number of corrosion days increases

As the corrosion increases, drop in PT signal with L(0,7) mode at 0.5 MHz is observed. Also mass loss increases with corrosion. Hence as the mass loss increases drop in voltage is observed.

Following observations are made from the above **Figure 6.10.6.9**

1) As the number of days of corrosion exposure for specimen increases uniform mass loss also increases at constant current.

2) Decrease in peak to peak voltage has been observed in 0.5MHz as the mass of pipe decreases due to corrosion.

6.5 CLOSURE

This chapter establishes that using specific guided waves modes for defect like corrosion is detectable. It is concluded that with the selected mode corrosion in pipes is detectable.

CHAPTER 7
CONCLUSIONS AND SCOPE OF FUTURE WORK

The experimental study carried out on pipes with simulated defects and corrosion damage shows the suitability of guided waves for detecting these damages. Different frequencies and modes have been explored to detect these damages in pipes. However, experimentally it has been established that lower frequencies exhibit better results as compared to higher frequencies. Conclusions of the study can be summarized as under.

7.1 NOTCH DEFECT STUDY

This study is carried out by inducing notch in the pipe. Three modes are used for detecting the notch damage L(0,7), L(0,12) and L(0,13). Following conclusions are drawn from this study:

- There is a drop in voltage amplitude with the increase in the depth of notch with all the three modes at selected frequencies.
- At 0.5 MHz frequency with L (0, 7) mode, decrease in voltage is consistent and regular as the depth of notch increases.
- For L(0,13) mode at 1 MHz, quick fall in voltage is observed at initial stage and sluggish response afterwards is noticed. Also signal is not found to be spreading in time as it interacts with the defect. This behavior restricts the further use of this mode for corrosion studies.
- With L(0,12) mode at 1 MHz, there is a visible drop in signal with increase in depth of the notch. But the fall in the signal with the varying extent of defect has been found to be irregular and disproportionate.

7.2 HOLE DEFECT STUDY

Circumferential hole is induced in the pipe. L(0,7) mode is used for detecting hole damage in pipe. Conclusions drawn from this study are:

- Voltage amplitude decreases as diameter of the hole increases. Shows that hole defect is detectable with L(0,7) mode.
- Diameter of the probe is a restrictive factor for detecting highly localized material loss in the form of the very small hole. Although as the size of hole increase, its delectability is found to be enhanced.

- Signatures are obtained circumferentially around the pipe and maximum voltage drop occurs at location of hole. Negligible drop in voltage at other location has been seen. However as the size of the hole increases, its effect can be seen in its circumferential vicinity.

7.3 CORROSION STUDY

Conclusions drawn from the corrosion study are

- There is fall in voltage amplitude with increase in corrosion exposure. It is because the area of pipe reduces and signal is consumed.
- In comparison to simulated machined notches, with clear area reduction, corrosion being non-uniform and widespread causes relatively less attenuation of signal.
- Initially signal fall is sluggish but later the fall is consistent. Maximum drop in voltage is observed at 30^{o}, 90^{o} and 120^{o} location of the pipe.

7.4 SCOPE OF FUTURE WORK

Non destructive testing techniques are becoming quite common these days. The field of NDT and damage detection constitutes important and challenging area of study. Guided waves provide efficient way of characterizing defects in cylindrical geometries. So, it becomes important to obtain reliable results from this technique and to find out better implementation of this technique. The experimental methodology discussed in this work can further extended for

- Scanning set up mechanism can be redesigned by fixing the pipe and rotating probe angle around the circumference of the pipe.
- At different stages of corrosion destructive testing can be done and correlated by residual life prediction.
- Ultrasonic testing using guided waves can be performed on different sizes and location of pipes.
- Analytical model can be developed and correlated with non destructive testing.
- Detection of welding defects and cracks can also be considered using guided waves.

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