

# **GUIDED WAVES FOR DAMAGE MONITORING IN PLATES FOR NOTCH AND CORROSION DEFECTS.**

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

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

By  
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**JULY 2012**

## CERTIFICATE

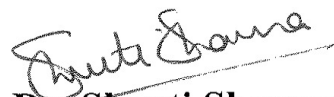
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I hereby certify that the work which is being presented in the thesis entitled, “GUIDED WAVES FOR DAMAGE MONITORING IN PLATES FOR NOTCH AND CORROSION DEFECTS”, in partial fulfillment of the requirement for the award of the “Masters of Engineering in CAD/CAM & ROBOTICS” submitted in the Mechanical Engineering Department, Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. Shruti Sharma, Assistant Professor, CED, Thapar University, Patiala .


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


  
(Ramandeep Singh)

This is to certify that above statement made by the candidate is correct and true to the best of my knowledge and belief.

  
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## ABSTRACT

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Non destructive testing techniques are the preferred techniques in this new era of development and progress. Also healthy monitoring of different mechanical and civil structures during its service is very important for the safety of human beings. Health monitoring of these structures using ultrasonic technique is an emerging field. It uses high frequency sound waves into the material to detect and locate defects, discontinuities in the material. This report presents the use of pulse echo technique of ultrasonic to detect, locate and quantify magnitude of defects such as notch, corrosion and correlate tensile stress with ultrasonic voltage by doing destructive tensile test.

In this whole study testing of mild steel plates was done in by pulse echo mode. The exact location of the defect and its change in magnitude as the percentage of defect increases was determined using this technique. Negative spike pulse is used as an input signal for sending and receiving signals through pulser/receiver system. The transducers were held in direct contact with the plate through a coupling medium (ultrasonic gel). The wave signatures obtained are analysed using digitizer card. The parametric study for notch defect was carried out by increasing the depth of notch and taking signatures at each stage. In case of corrosion study testing of plate was done after corroding plate by impressed current corrosion and signatures were taken at different stages of corrosion. For correlation of ultrasonic with tensile stress, both ultrasonic testing and destructive tensile testing was done for different specimens having different percentage of defect and a generalized trend was obtained. Final results obtained were reported in the form of voltage-time curves. For different damage types, most ideal modes and frequencies were selected for testing.

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## INTRODUCTION

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### 1.1 GENERAL

Structural health monitoring (SHM) is a key development that is driving a revolution in smart-structures technologies. Promising quantum gains in the performance and cost effective maintenance of high value assets such as aircraft, civil infrastructure, and structural health monitoring technology will be an integral component of an increasing number of future engineering structures. The rapid advances that have been made in the past two decades in sensor technology, multifunctional materials and innovative structural concepts are now leading into the practical use of Structural Health Monitoring. It is estimating the state of structural health, for detecting the changes in structure that affect its performance. Two major factors that are considered in SHM are time scale of change which deals how quickly the change occurs and severity of change which deals the degree of change.

Global technique and local technique are two different techniques are available to assess the health of structure. In global technique dynamic characteristics of structure are used to identify the damage, its approximate location and its severity, reducing the need for manual inspection. Local techniques are used most widely for assessing the health of the mechanical structures.

### 1.2 OBJECTIVES OF PRESENT STUDY

As the design and construction of metal plate structures, machines and vessels continue to evolve, it is becoming imperative that these structures be monitored for their health. In order to meet this need, the discipline of Structural Health Monitoring (SHM) has emerged. It involves the application of wave propagation in metal plates and aims to assist engineers in realizing the full benefits of structural health monitoring. Health of several structures is monitored by recording propagation of stress waves through them. The wave characteristics change due to the deterioration or defects in the metal plate structure and they are sensitive to the location, extent and character of damage. However, for a successful monitoring a prior knowledge of the wave characteristic due to different cases is needed to be studied.

The overall objectives of the present study are:

- Review of literature on propagation of ultrasonic waves through plates.
- Generate and investigate the propagation of ultrasonic guided waves through the healthy plate and plate with simulated notch damages. Two specimens; one having notch on one side of plate i.e. asymmetrical notch and other having notch on both sides i.e. symmetrical notch.
- Develop a damage monitoring strategy in plates using ultrasonic guided waves. Calibrate the ultrasonic results with established existing in situ strength measurement parameters.
- Characterize actual corrosion in mild steel plates and its extent through the analysis and comparison of wave signatures of healthy and corroded mild steel plates.

## 1.3 DAMAGES IN PLATES

### 1.3.1 Definition of Damage

In the most general terms, damage can be defined as changes introduced into a system that adversely affects its current or future performance. Implicit in this definition is the concept that damage is not meaningful without a comparison between two different states of the system, one of which is assumed to represent the initial or healthy and often undamaged state. This thesis is focused on the study of damage identification in plate structures; therefore, the definition of damage will be limited to changes to the material and/or geometric properties of these systems. As an example, a crack that forms in a mechanical part produces a change in geometry that alters the stiffness characteristics of that part. Depending on the size and location of the crack and the loads applied to the system, the adverse effects of this damage can be either immediate or may take some time before they alter the system's performance. In terms of *length scales*, all damage begins at the material level and then under appropriate loading scenarios progresses to component and system level damage at various rates. In terms of *time scales*, damage can accumulate incrementally over long periods of time such as that associated with fatigue or corrosion damage accumulation.

The damage state is described by answering the following questions:

- 1) Is there damage in the system (existence)?
- 2) Where is the damage in the system (location)?
- 3) What kind of damage is present (type)?
- 4) How severe is the damage (extent)?
- 5) How much useful life remains (prognosis)?

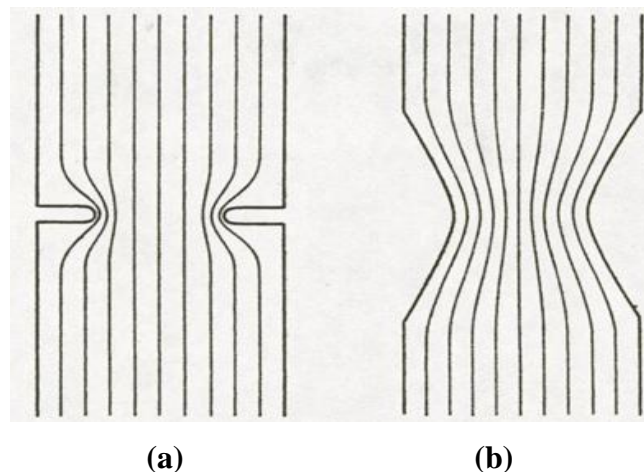
The statistical models are used to answer these questions in an unambiguous and quantifiable manner. Experimental structural-dynamics techniques can be used to address the first two questions in either an unsupervised or supervised learning mode. To identify the type of damage, data from structures with the specific types of damage must be available for correlation with the measured features and, hence, a supervised learning approach must be taken. Analytical models are usually needed to answer the fourth and fifth questions unless examples of data are available from the system (or a similar system) when it exhibits varying damage levels. Therefore, the fourth and fifth questions must be addressed in a supervised learning mode.

### 1.3.2 Damage in Plates

Mild steel plates of different thickness have very wide application in mechanical structures, machines, pressure vessels, naval vessels etc. So due to there wide applications these are exposed to various kinds damages which can be summarized as

- 1) Notches/cracks
- 2) Corrosion

1) **Notch Defect:** - An indentation or incision on an edge or surface is called notch. For qualitative estimates we can use an analogy between stresses or strains and liquid flow. Restrictions or enlargements in a pipe produce local increases in flow velocity somewhat similar to the local increases in stresses produced by changes in cross section. As shown in **figure 1.1 (a)** and **(b)** the large section and the small section are the same in both cases, but the transitions are different.



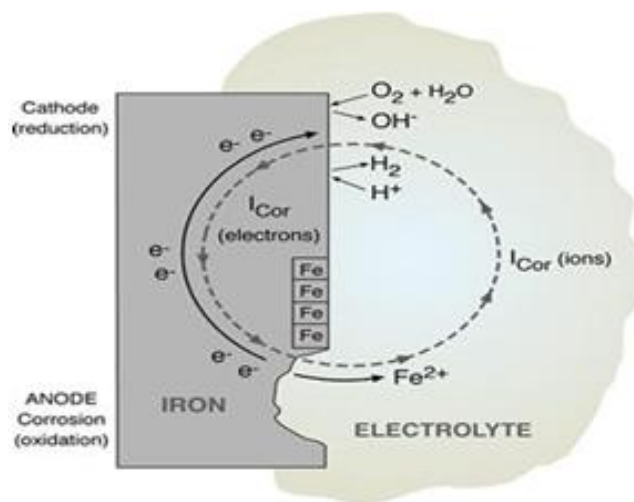
**Figure 1.1: The crowding and bending of flow lines near obstructions help to visualize the concentration of stresses and strains near notches. [1]**

Notch can be considered as a resemblance to crack defect in actual practice. Cracks in actual practice occur due to fatigue, stress corrosion, and weld defects. These have great impact on various physical properties such as tensile and compressive strength of given material. **Figure 1.2** shows the crack defect on a cylindrical surface



**Figure 1.2: crack defect on a cylindrical surface [1]**

- 2) **Corrosion:** - Corrosion is the deterioration of materials by chemical interaction with their environment. The term corrosion is sometimes also applied to the degradation of plastics, concrete and wood, but generally refers to metals.



**Figure 1.3: Corrosion Mechanism [1]**

The chemical interaction of material with environment is clearly depicted in **figure 1.3**.

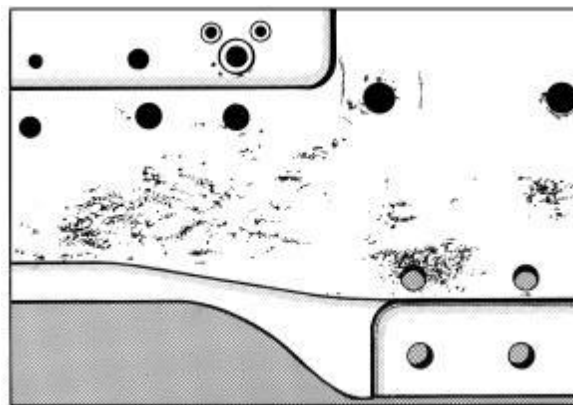
### **Effects of corrosion**

Losses are economic and safety:

- Reduced Strength
- Downtime of equipment
- Escape of fluids
- Lost surface properties
- Reduced value of goods

### **Various types of corrosion [2]**

- 1) **General surface corrosion:** - General surface corrosion (also referred to as Uniform Etch or Uniform Attack Corrosion) is the most common form of corrosion and results from a direct chemical attack on a metal surface and involves only the metal surface.
- 2) **Pitting corrosion:** - Pitting corrosion is one of the most destructive and intense forms of corrosion. It can occur in any metal but is most common on metals that form protective oxide films, such as aluminum and magnesium alloys. It is first noticeable as a white or gray powdery deposit, similar to dust, which blotches the surface as shown in **figure 1.4**. When the deposit is cleaned away, tiny holes or pits can be seen in the surface. These small surface openings may penetrate deeply into structural members and cause damage completely out of proportion to its surface appearance.



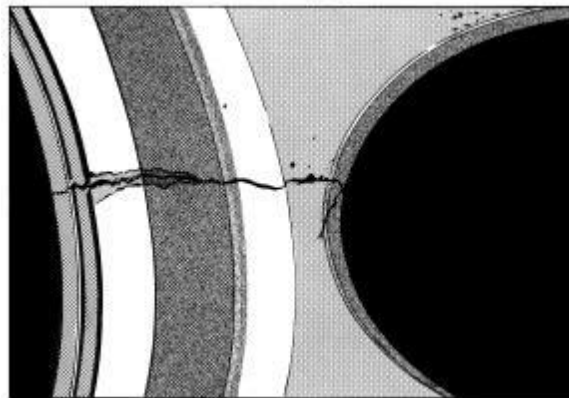
**Figure1.4: Pitting corrosion [2]**

- 3) **Galvanic corrosion:** - Galvanic corrosion occurs when two dissimilar metals make contact in the presence of an electrolyte. It is usually recognizable by the presence of a build-up of corrosion at the joint between the metals.

4) **Stress corrosion cracking:** - This form of corrosion involves constant or cyclic stress, acting in conjunction with a damaging chemical environment. The stress may be caused by internal or external loading.

a) **Internal stress may be trapped** in a part of structure during manufacturing processes such as cold working or by unequal cooling from high temperatures. Most manufacturers follow up these processes with a stress relief operation. Even so, sometimes stress remains trapped. The stress may be externally introduced by riveting, welding, bolting, clamping, press fit, etc. If a slight mismatch occurs, or a fastener is over-torqued, internal stress will be present.

b) **Internal stress is more important** than design stress, because stress corrosion is difficult to recognize before it has overcome the design safety factor. The level of stress varies from point to point within the metal as in **figure 1.5**. Stresses near the yield strength are generally necessary to promote stress corrosion cracking. However, failures may occur at lower stresses. Specific environments have been identified which cause stress corrosion cracking of certain alloys.



**Figure 1.5: Stress corrosion cracking [2]**

5) **Fatigue corrosion:**-Fatigue corrosion involves cyclic stress and a corrosive environment. Metals may withstand cyclic stress for an infinite number of cycles so long as the stress is below the endurance limit of the metal. Once the limit has been exceeded, the metal will eventually crack and fail from metal fatigue. However, when the part or structure undergoing cyclic stress is also exposed to a corrosive environment, the stress

level for failure may be reduced many times. Thus, failure occurs at stress levels that can be dangerously low depending on the number of cycles assigned to the life-limited part.

- 6) Fretting corrosion:-**Fretting corrosion, (also known as wear corrosion or friction oxidation) can occur at the interface of two highly-loaded surfaces which are not supposed to move against each other. However, vibration may cause the surfaces to rub together resulting in an abrasive wear known as fretting. The protective film on the metallic surfaces is removed by this rubbing action. With continued rubbing, metal particles sheared from the surface of the metal combine with oxygen to form metal oxide. As these oxides accumulate, they cause damage by abrasive action and increased local stress. The most common example of fretting corrosion is the smoking rivet found on engine cowling and wing skins. This is one corrosion reaction that is not driven by an electrolyte, and in fact, moisture may inhibit the reaction.

#### **1.4 NON DESTRUCTIVE TESTING (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 19<sup>th</sup> and 20<sup>th</sup> century resulted in early rapid developments in NDT techniques. During the earlier days, the primary purpose was the detection of defects. 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.

In the early 1970's, 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. In industry, nondestructive testing can do so much more. It can effectively be used for the:

1. Examination of raw materials prior to processing
2. Evaluation of materials during processing as a means of process control
3. Examination of finished products
4. Evaluation of products and structures once they have been put into service

### **1.5 CONDITIONS FOR EFFECTIVE NDT**

There are many variables associated with nondestructive testing that must be controlled and optimized. The following are major factors that must be considered in order for a nondestructive test to be effective.

- **The product must be testable:** There are limitations inherent with each of the nondestructive test methods and it is essential that these limitations be known so that the appropriate method is applied based on the variables associated with the test object. For example, it would be very difficult to provide a meaningful ultrasonic test on a small casting with very complex shapes and rough surfaces. In this case, it would be much more appropriate to consider radiography. In another case, the object may be extremely thick and high in density, making radiography impractical. Ultrasonic testing, on the other hand, may be very effective. In addition to the test object being “testable,” it must also be accessible.
- **Approved procedures must be followed:** It is essential that all nondestructive examinations be performed following procedures that have been developed in accordance with the requirements or specifications that apply. In addition, it is necessary to qualify or “prove” the procedure to assure that it will detect the applicable discontinuities or conditions and that the part can be examined in a manner that will satisfy the requirements. Once the procedure has been qualified, a certified NDT Level III individual or other quality assurance person who is suitably qualified to properly assess the adequacy of the procedure should approve it.

- **Equipment is operating properly:** All equipment to be used must be in good operating condition and properly calibrated. In addition, control checks should be performed periodically to assure that the equipment and accessory items are functioning properly. Annual calibrations are usually required but a “functional” check is necessary as a prerequisite to actual test performance.
- **Documentation must be complete:** It is essential that proper test documentation be completed at the conclusion of the examination. This should address all of the key elements of the examination, including calibration data, equipment and part description, procedure used, identification of discontinuities if detected, etc. In addition, the test documentation should be legible. There have been cases where the examination was performed properly and yet the documentation was so difficult to interpret that it cast doubt on the results and led to concerns regarding the validity of the entire process.
- **Personnel are qualified:** Since nondestructive testing is a “hands-on” technology and depends greatly on the capabilities of the individuals performing the examinations, personnel must not only be qualified, but also properly certified. Qualification involves formalized planned training, testing, and defined experience.

## **1.6 NON DESTRUCTIVE VERSUS DESTRUCTIVE TESTS**

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
- Yield point
- Ductility
- Elongation characteristics
- Fatigue life
- Corrosion resistance

- Toughness
- Hardness
- Impact resistance

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. Another destructive test commonly used to measure materials resistance to impact is the Charpy test. In this test, a specimen that is usually notched is supported at one end and is broken as a pendulum is released and impacts in the region of the notch. The measure of the material's resistance to impact (or notch toughness) is determined by the subsequent rise of the pendulum.

Hardness is also an important material characteristic. The hardness test (See Figure 1-18) measures the material's resistance to plastic deformation. There has always been a minor dispute as to whether this test was nondestructive or destructive, since there usually is an indentation made on the surface of the material. If the hardness test is done without indentation (as is the case when using eddy currents or ultrasonic), it can be considered truly "nondestructive." Although it is assumed in many cases that the test specimen is representative of the material from which it has been taken, it cannot be said with 100% reliability that the balance of the material will have exactly the same characteristics as that test specimen. Key benefits of destructive testing include:

- 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.

Limitations of destructive testing include:

- 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.

Benefits of nondestructive testing include:

- 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.

Limitations of nondestructive testing include:

- 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.

## 1.7 TECHNIQUES FOR NDT

The aim of all NDT techniques is to detect and locate defects, without causing any damage to the component under inspection. Some of the most commonly used NDT techniques like visual and optical testing, penetrant testing, electromagnetic testing are used for testing only surface defects, while techniques such as radiography and ultrasonic testing are used to detect both surface and buried-in defects.

Some of the commonly used NDT techniques are as follows:-

- **Visual and Optical Testing:** Visual inspection involves using an inspector's eyes to look for defects. The inspector may also use special tools such as magnifying glasses or mirrors gain access and more closely inspect the subject area.
- **Penetrant Testing:** Test specimens are coated with visible or fluorescent dye solution. Excess dye is then wiped out from the surface, and a developer is applied. The developer acts as blotter, drawing trapped penetrant out of imperfections open to the surface. With visible dyes, vivid color contrasts between the penetrant and developer make “bleed out” easy to see. **Figure 1.6** depicts the dye Penetrant testing technique.

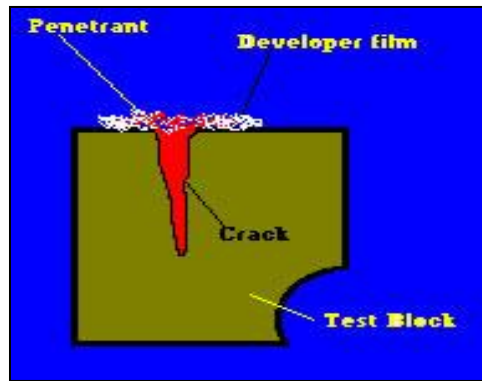


Figure 1.6: Dye Penetrant test

- Magnetic Particle Testing (MT):** In this method a magnetic field in a ferromagnetic material is induced as in **figure 1.7(a)** and then dusting the surface with iron particles (either dry or suspended in liquid) is done. Surface and near-surface imperfections distort the magnetic field and concentrate iron particles near imperfections as in **figure 1.7(b)** providing a visual indication of the flaw.

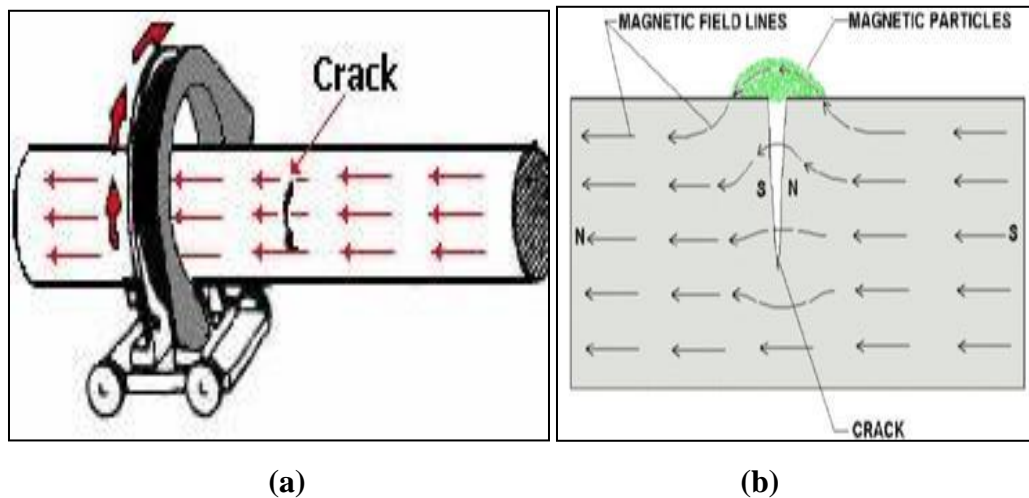
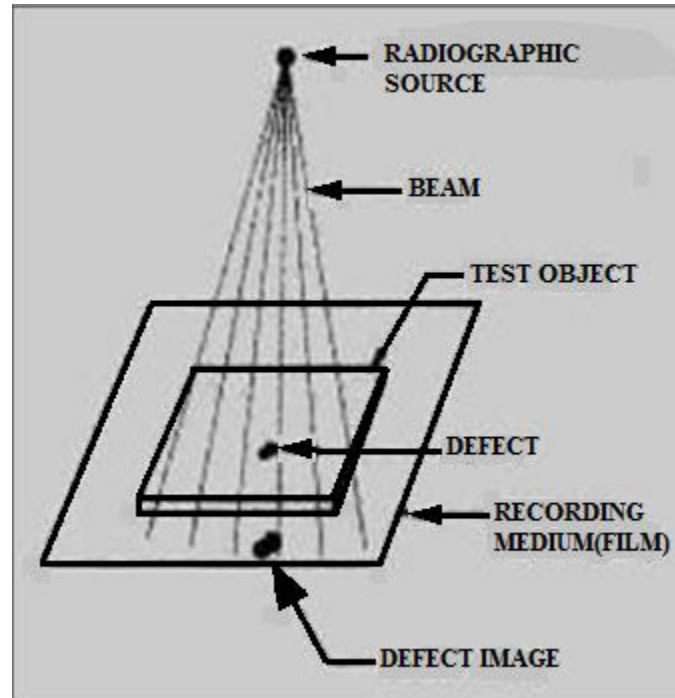


Figure 1.7: Magnetic Particle Testing

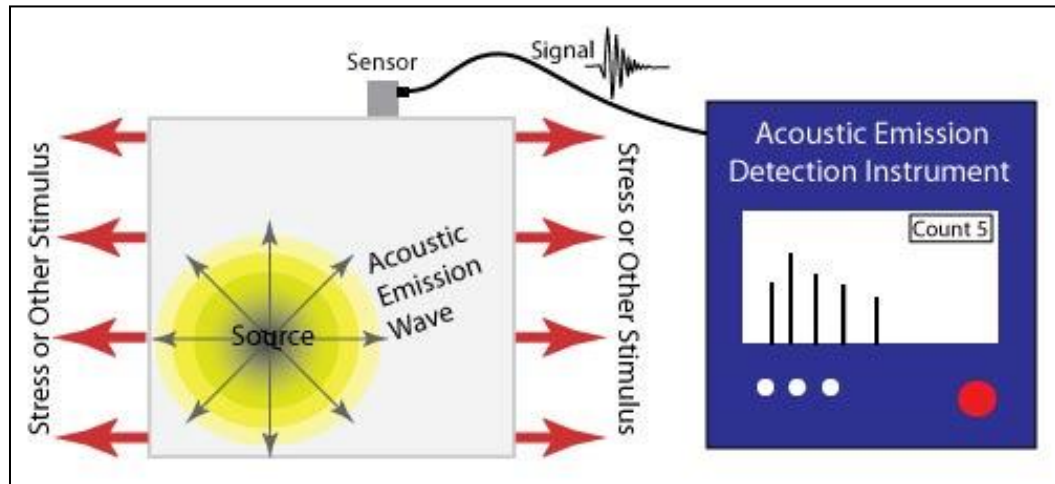
- Electromagnetic Testing (ET) or Eddy Current Testing:** Eddy currents are generated in a conductive material by an induced alternating magnetic field and they flow in circles at just below the surface of the material. Interruptions in the flow of eddy currents, caused by imperfections, dimensional changes, or changes in the materials conductive and permeability properties, can be detected with the proper equipment.
- Radiography (RT):** Radiography involves the use of penetrating gamma or X radiation to examine parts and products for imperfections. An X-ray generator or radioactive

isotope is used as a source of radiation. The resulting shadowgraph shows the dimensional features of the part. Possible imperfections are indicated as density changes as shown in **figure 1.8** on the film in the same manner as medical X-ray shows broken bones.



**Figure 1.8: Radiography**

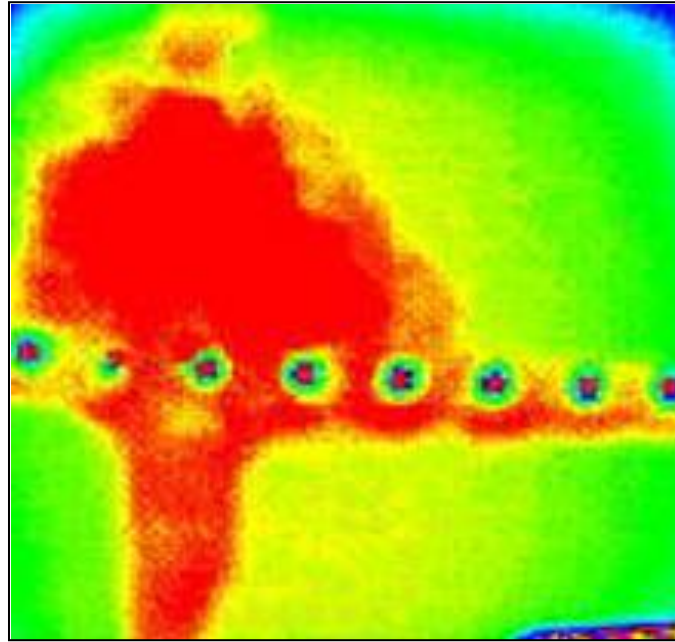
- **Ultrasonic Testing (UT):** Ultrasonic testing use transmission of high-frequency sound waves into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo, wherein sound is introduced into a test object and reflections (echoes) are returned to a receiver from internal imperfections or from the part's geometrical surfaces. These testing can be used for detecting various surface as well as internal defects.
- **Acoustic Emission Testing (AE):** When a solid material is stressed, imperfections within the material emit short bursts of acoustic energy called "emissions." as in ultrasonic testing; acoustic emissions can be detected by special receivers. **Figure 1.9** shows acoustic emission wave propagation. Emission sources can be evaluated through the study of their intensity, rate, and location.



**Figure 1.9: Acoustic Emission Testing**

- **Leak Testing (LT):** Several techniques are used to detect and locate leaks in pressure containment parts, pressure vessels, and structures. Leaks can be detected by using electronic listening devices, pressure gauge measurements, liquid and gas Penetrant techniques, and/or a simple soap-bubble test.
- **Electromagnetic Acoustic Transducers (EMATs):** They generate and detect ultrasonic waves via electromagnetic coupling between the EMAT and the metal samples. They operate via the Lorentz force or magneto elastic mechanisms or both simultaneously.
- **X-Ray Fluorescence (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.
- **Infrared Thermography:** It is a fast NDT inspection method which does not influence the process and maps the temperature differences of any object in a range from -50°C to 1500°C. Instead of detecting the temperature point by point, thermo graphic camera is

able to detect the temperature across a complete surface. This gives an excellent image of local temperature differences. A thermographic image is shown in **figure 1.10**. However this technique is suitable for the components having thermal variations. This technique has limited applicability.



**Figure 1.10: Infrared Thermography**

### **1.8 CHOICE OF NDT METHOD**

When it is possible to use several inspection techniques, the choice of a specific technique will depend on the accuracy and cost of the inspection, balancing the money spent on safety measures with the business return of the system being maintained. The accuracy of a given technique must also be sufficient to detect defects considerably smaller than those that could result in failure because these defects can grow in size between inspections. The diverse nature of different NDT processes results in different sources of variance and possible impact on detection output capabilities. It is important to recognize the source and nature of variance in each NDT process and to take such information into consideration when applying margins to the NDT processes.

The NDT methods and procedures are selected using a variety of practical implementation criteria, are represented in **Table 1.1**. It is important to determine the

optimum NDT technique for various defects and there applicability for different physical structures.

**Table 1.1 Comparative analyses of various NDT techniques [3]**

| <b>Parameter</b>                        | <b>Penetrant Testing</b>  | <b>Magnetic Particle Testing</b>   | <b>Ultrasonic Testing</b>   | <b>Eddy Current Testing</b>                      | <b>Radiographic Testing</b>                      |
|---|---|--|---|--|--|
| <b>Range of Inspection</b>              | 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.  |
| <b>Geometry of part to be inspected</b> | Parts with complex geometry are routinely inspected.  | Can detect surface and subsurface flaws.   | Only single sided access is required.                                 | Test probe does not need to contact the part.    | Detects surface and subsurface defects.          |
| <b>Geometry of part to be inspected</b> | Indications are produced directly on surface of the part providing a visual image of the discontinuity. | Indications are produced directly on the surface of the part and form an image of the discontinuity. | Provides distance information.  | Method can be used for more than flaw detection. | Method can be used for more than flaw detection. |
| <b>Cost of inspection</b>               | Low   | Low  | Low   | Low  | Moderate   |
| <b>Cost of equipment</b>                | Low   | Moderate   | Moderate  | High   | High   |
| <b>Surface preparation</b>              | Surface preparation is critical.  | Surface preparation is less critical.  | Minimum part preparation is required.                                 | Minimum part preparation is required.            | Minimum part preparation is required.            |

## DISADVANTAGES

| <b>Parameter</b>                        | <b>Penetrant Testing</b>                            | <b>Magnetic Particle Testing</b>                           | <b>Ultrasonic Testing</b>   | <b>Eddy Current Testing</b>  | <b>Radiographic Testing</b>  |
|---|---|--|---|--|--|
| <b>Type of material to be inspected</b> | Detects only surface breaking defects.              | Only ferromagnetic materials can be inspected.             | Surface must be accessible to probe and couplant.                 | Only conductive materials can be inspected.  | Extensive operator training and skill required.                          |
| <b>Type of surface needed</b>           | 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.               |
| <b>Exceptions in detection</b>          | Sub-surface defects go undetected.                  | Large currents are needed for very large parts.            | Linear defects oriented parallel to sound beam can't be detected. | Flaws that lie parallel to the inspection probe coil winding direction can go undetected | Orientation of the radiation beam to non volumetric defects is critical. |
| <b>Post inspection treatment</b>        | Post cleaning is necessary to remove chemicals.     | Demagnetization and post cleaning is usually necessary.    | Thin parts may be difficult to inspect.                           | Surface finish and roughness may interfere.  | Inspection of thick section can be time consuming.                       |
| <b>Personnel needed</b>                 | Requires multiple operations                        | Skill and trained staff is required.                       | Skill required is more  | Skill and trained staff is required.   | Skill and trained staff is required.                                     |

### 1.9 NDT TECHNIQUE SELECTION

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 cost effectiveness of the technique must also be taken into consideration. **Table 1.2** provides some guidance in the selection of NDT techniques for common flaw detection and measurement applications.

**Table 1.2 Selections of NDT Techniques**

| Flaw type \ Method                           | Visual Magnetic particle* | Dye penetrant | Magnetic particle* | Ultrasonic | Eddy current** | x- ray |
|--|---------------------------|---------------|--------------------|------------|----------------|--------|
| Surface breaking Linear                      | 1                         | 3             | 3                  | 2          | 3              | 1      |
| Surface breaking Volumetric                  | 3                         | 3             | 3                  | 3          | 3              | 3      |
| Near surface, linear and parallel to surface | 0                         | 0             | 2                  | 2          | 3              | 1      |
| Near surface, linear and normal to surface   | 0                         | 0             | 0                  | 3          | 0              | 0      |
| Near surface volumetric                      | 0                         | 0             | 2                  | 3          | 3              | 3      |
| Sub-surface linear and normal to surface     | 0                         | 0             | 0                  | 2          | 0              | 1      |
| Sub-surface linear and parallel to surface   | 0                         | 0             | 0                  | 3          | 0              | 1      |
| Subsurface Volumetric                        | 0                         | 0             | 0                  | 3          | 0              | 3      |

\* Ferromagnetic materials only \*\* Conductive materials only

(0) Will Not Detect (1) Not Well Suited (2) Fairly Suitable (3) Ideal Application

From the above comparison between various techniques, it is concluded that Ultrasonic Waves being capable of detecting most of surface and sub-surface defects. It is cost effective and no

special training required for the personnel. It has no safety hazard and can be used for damage detection in plate structures efficiently.

### **1.10 CONCLUDING REMARKS**

This chapter gives a background of Structural health monitoring using non destructive techniques. Major factors that are to be controlled for effective non destructive testing are also discussed. A brief description of various NDT techniques is given. This chapter also gives the potential of ultrasonic technique for damage detection in plate structures. This chapter gives the details of various types of defects in plates with the main focus on corrosion and notch defect.

## CHAPTER 2

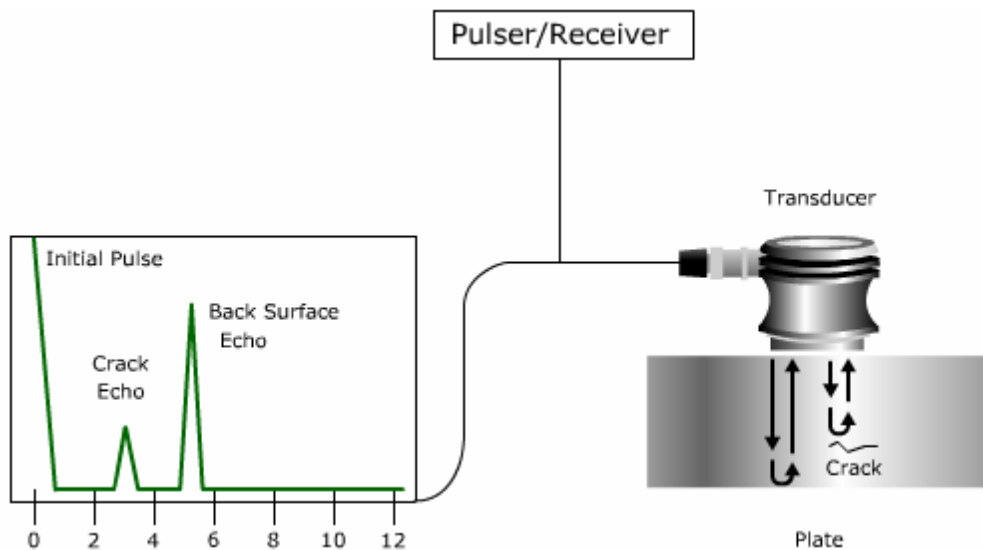
### ULTRASONICS FOR DAMAGE DETECTION

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#### 2.1 GENERAL

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

**Figure 2.1** gives information about setup of ultrasonic testing in flaw detection.



**Figure 2.1: Principle of ultrasonic [4]**

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

from the time of flight of received signal ( $t$ ) and knowing the velocity ( $v$ ) of wave in a particular solid medium, the defect can be located as  $D = (v \times t) / 2$ . This is called pulse echo technique. It is assisted by through transmission in which two transducer are used for testing the object specimen. The magnitude of damage is found from the change in amplitude of the through transmission signal. This is one of the best non-destructive testing methods where ultrasonic wave is send into the structure to find the location and magnitude of the defect. Ultrasonic wave propagation varies with change in the medium in which the wave propagates.

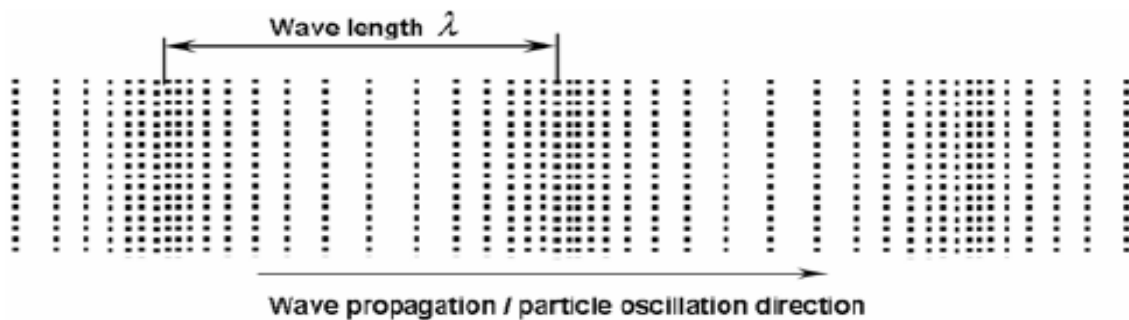
## 2.2 MODES OF WAVE PROPAGATION

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

1. Longitudinal or Compressional waves (L-waves).
2. Transverse or Shear waves (S-waves)
3. Surface or Rayleigh waves.
4. Lamb or Plate waves
5. Creeping or Head waves

### 2.2.1 Longitudinal or Compressional waves

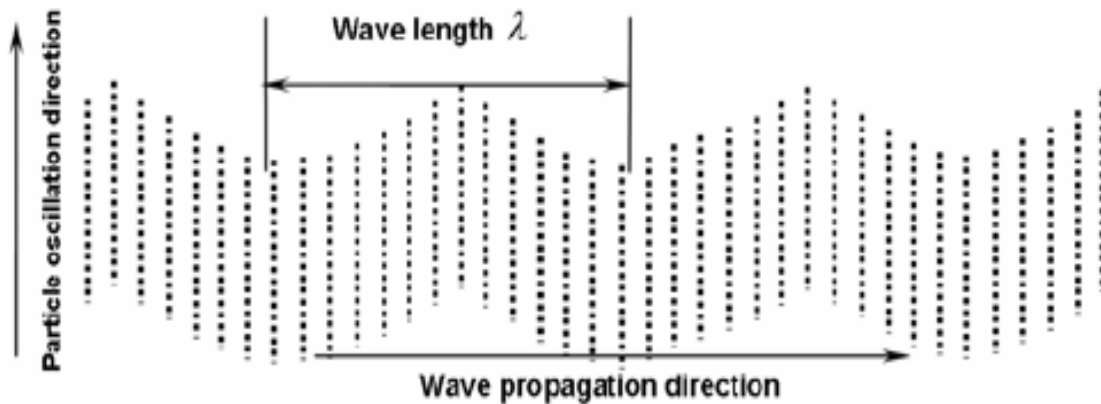
In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation as shown in the **Figure 2.2**. Since compressional and dilatational forces are active in these waves, they are also called pressure or compressional waves. They are also sometimes called density waves because their particle density fluctuates as they move. Compression waves can be generated in liquids, as well as solids because the energy travels through the atomic structure by a series of compression and expansion (rarefaction) movements.



**Figure 2.2: Propagation of Longitudinal waves [5]**

### 2.2.2 Transverse or Shear wave

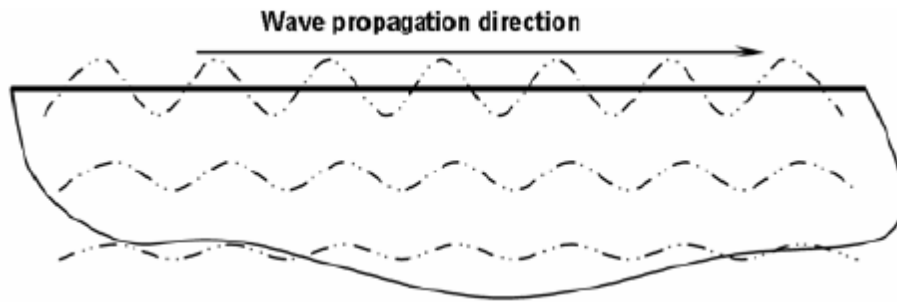
In the transverse or shear wave, the particles oscillate at a right angle or transverse to the direction of propagation as shown in the **figure 2.3**. Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves. In fact, shear waves are usually generated in materials using some of the energy from longitudinal waves. For the propagation of transverse waves, it is necessary that each particle exhibits a strong force of attraction to its neighbors, so that as a particle moves back and forth it pulls its neighbor with it. Due to this reason air and water do not support transverse waves. In gases, the forces of attraction between molecules are so small that shear waves cannot be transmitted. The same is true of a liquid, unless it is particularly viscous or is present as a very thin layer. The velocity of transverse waves is approximately 50% of the longitudinal wave velocity for the same material.



**Figure 2.3: Propagation of Transverse waves [5]**

### 2.2.3 Surface (or Rayleigh) waves

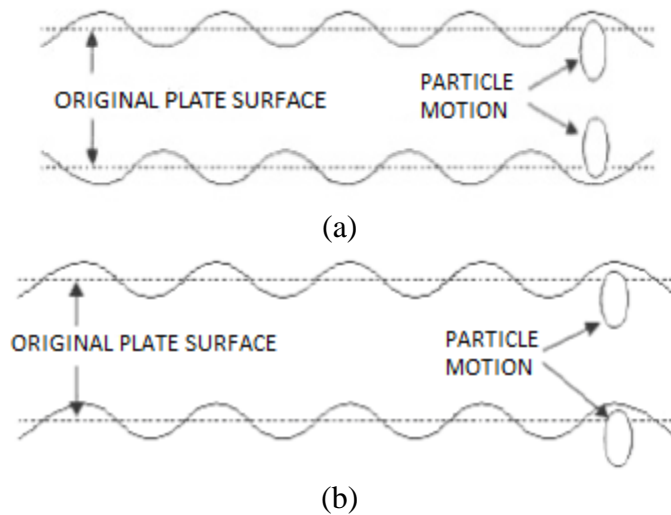
Surface (or Rayleigh) waves travel on the surface of a relatively thick solid material penetrating to a depth of one wavelength. Rayleigh waves are useful because they are very sensitive to surface defects and they follow the surface around curves as shown in **figure 2.4**. These waves can travel along the flat and curved surfaces. These waves are subjected to less attenuation in a given material than the longitudinal or transverse waves. Because of this, Rayleigh waves can be used to inspect areas that other waves might have difficulty reaching.



**Figure 2.4: Propagation of surface waves [5]**

### 2.2.4 Lamb waves

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



**Figure 2.5: Lamb Wave mode (a) Symmetric (S mode) (b) Anti-symmetric (A mode) [6]**

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

mode” because a large portion of the motion moves in a normal direction to the plate, and a little motion occurs in the direction parallel to the plate. In this mode, the body of the plate bends as the two surfaces move in the same direction.

### **2.2.5 Creeping waves**

These waves are also called head waves. The behavior of creeping waves is similar to that of longitudinal waves. They travel as fast as longitudinal waves and the creeping waves should not be misunderstood as moving slowly. These are generated parallel to scanning surface, enabling detection of surface breaking defects. These have limited range and as these travel just below the surface and not on the surface, so the couplant has no influence. Lamb waves are most preferred waves for the ultrasonic testing in damage detection in steel plates, since the lamb waves propagate only in very thin metals. Symmetric lamb waves are used to find the damage in normal plates whereas anti symmetric lamb waves are used to find the damage in plates with the bend.

## **2.3 REFLECTION, REFRACTION AND MODE CONVERSION**

When sound travels in a solid material, one form of wave energy can be transformed into another form. For example, when a longitudinal wave hits an interface at an angle, some of the energy can cause particle movement in the transverse direction to start a shear (transverse) wave. Mode conversion occurs when a wave encounters an interface between materials of different acoustic impedances and the incident angle is not normal to the interface. When sound waves pass through an interface between materials having different acoustic velocities, refraction takes place at the interface. The larger the difference in acoustic velocities between the two materials, the more the sound is refracted. Notice that the shear wave is not refracted as much as the longitudinal wave. This occurs because shear waves travel slower than longitudinal waves. Therefore, the velocity difference between the incident longitudinal wave and the shear wave is not as great as longitudinal waves but it is between the incident and refracted longitudinal waves. Also note that when a longitudinal wave is reflected inside the material, the reflected shear wave is reflected at a smaller angle than the reflected longitudinal wave. This is also due to the fact that the shear velocity is less than the longitudinal velocity within a given material. Snell's Law holds true for shear waves as well as longitudinal waves and can be written as follows.

Where:

VL1 - is the longitudinal wave velocity in material 1

VL2 - is the longitudinal wave velocity in material 2

VS1 - is the shear wave velocity in material 1

VS2 - is the shear wave velocity in material 2

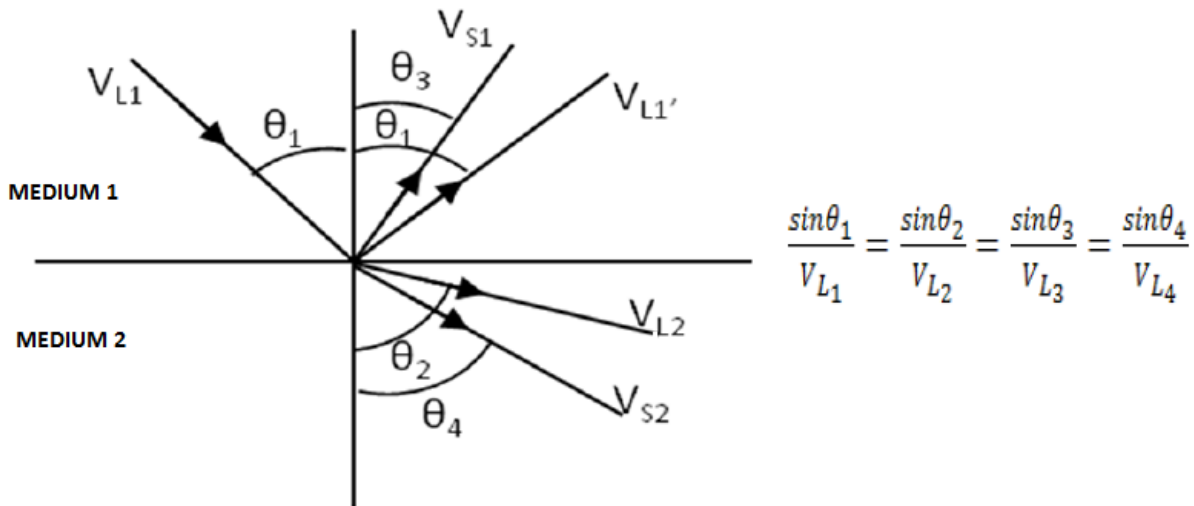


Figure 2.6: Snell's Law [7]

## 2.4 CRITICAL ANGLE

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. 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.

### 2.4.1 First Critical Angle

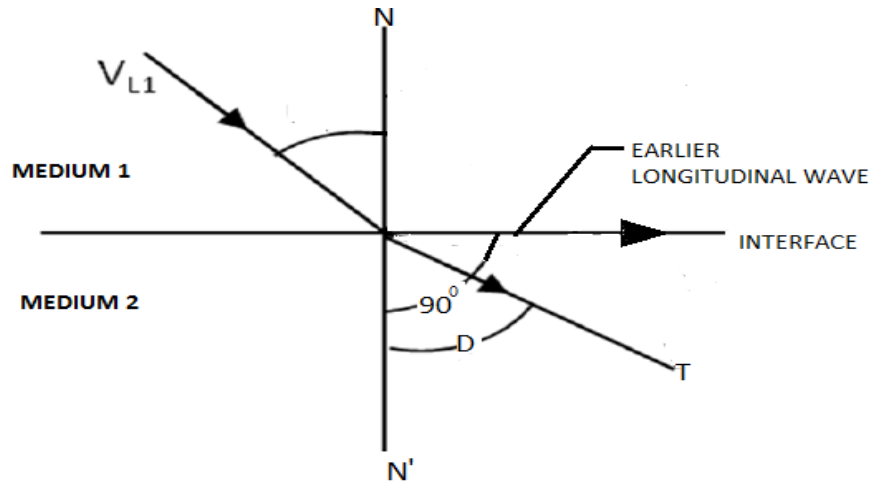
If the angle of incidence A is increased in the particular case when  $c_2 > c_1$ , angle B of the refraction longitudinal wave also increases till, for some specific value of angle A, the angle B becomes equal to  $90^\circ$ . At this angle ( $A_1$ ) there would be no refraction longitudinal wave in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

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

Or

$$A_1 = \sin^{-1}(c_1/c_2)$$

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



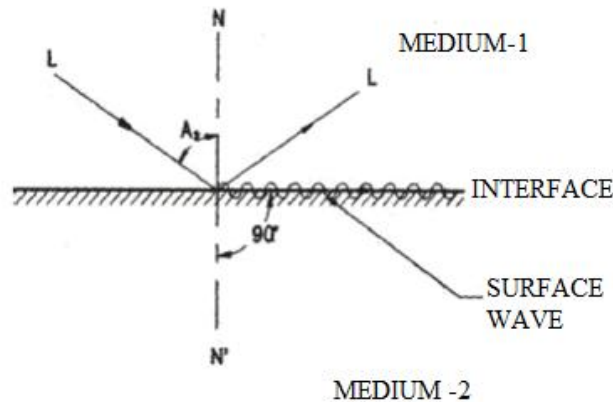
**Figure 2.7: First Critical Angle [7]**

### 2.4.2 Second Critical Angle

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

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

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



**Figure 2.8: Second Critical Angle [7]**

The **Figure 2.8** shows the formation of Second Critical Angle. At this position there would be no sound beam entering the medium 2 and the shear wave would appear as surface wave.

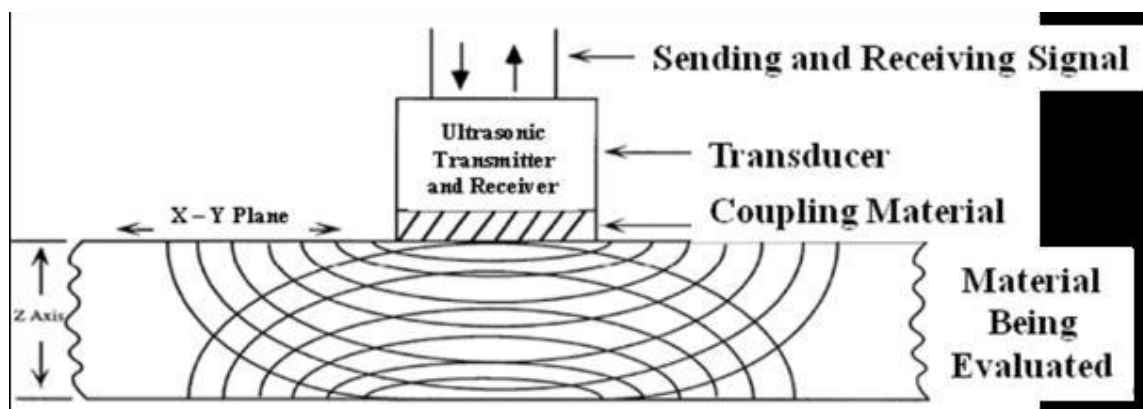
## 2.5 METHODS OF ULTRASONIC TESTING

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. Following are the three methods generally used:

1. Pulse Echo Method.
2. Through Transmission Method
3. Two transducer method
4. Resonance method

### 2.5.1 Pulse Echo Method

In the pulse-echo method, a piezoelectric transducer with its longitudinal axis located perpendicular to and mounted on or near the surface of the test material is used to transmit and receive ultrasonic energy, as shown in **Fig. 2.9**. The ultrasonic waves are reflected by the opposite face of the material or by discontinuities, layers, voids, or inclusions in the material, and received by the same transducer, where the reflected energy is converted into an electrical signal as shown in the Figure. The electrical signal is computer processed for display on a video monitor or TV screen. The display can show the relative thickness of the material, depth into the material where flaws are located, and (with proper scanning hardware and software), where the flaws are located in the X-Y plane.



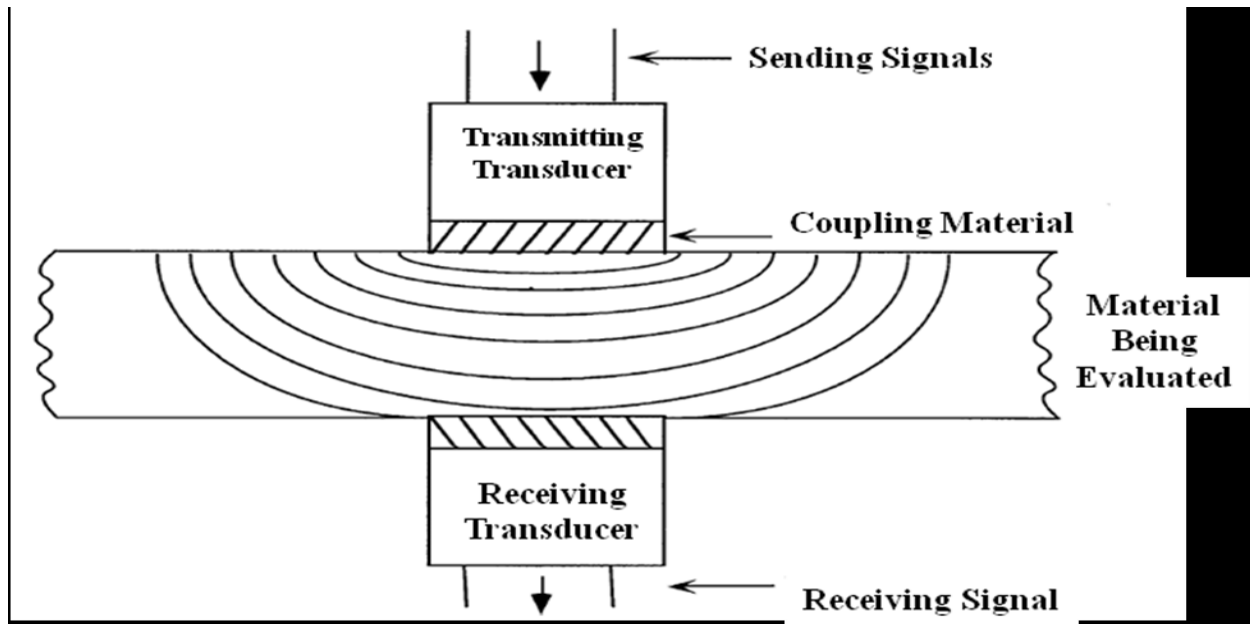
**Figure 2.9: Pulse Echo Method [8]**

### 2.5.2 Two Transducer Method

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

### 2.5.3. Through Transmission Method

In the through-transmission method, an ultrasonic transmitter is used on one side of the material while a detector is placed on the opposite side as shown in the **Fig. 2.10**. One unit acts as transmitter and the other unit as receiver. The beam from the transmitter T travels through the material to its opposite surface where the receiving transducer R is placed. Scanning of the material using this method will result in the location of defects, flaws, and inclusions in the X-Y plane.



**Figure 2.10: Through Transmission Method [8]**

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

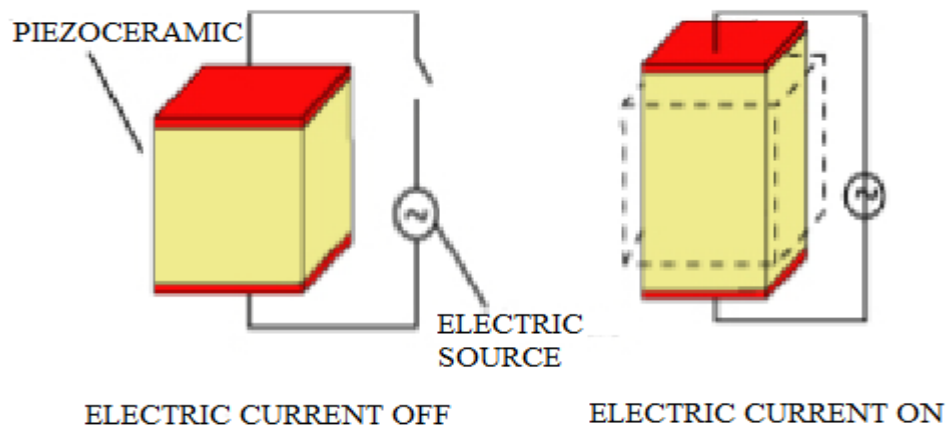
Echo method is mostly used in Ultrasonic testing to find location of defect in specimen and Through Transmission is mostly used in testing using ultrasonic's to find the magnitude of the defect in Specimen.

#### 2.5.4 Resonance Method

The method uses resonance phenomenon to measure the material thickness or to determine the quality of bonding, in two materials. In a situation that the thickness of the material equals half the wavelength of the sound or it's multiple, resonance takes place. The frequency of the continuous longitudinal waves transmitted in the material is varied till standing waves are set up in the material.

#### 2.6 PIEZOELECTRIC TRANSDUCERS FOR ULTRASONIC WAVE GENERATION

The conversion of electrical pulses to mechanical vibrations and the conversion of returned a mechanical vibration back into electrical energy is the basis for ultrasonic testing. The active element is the heart of the transducer as it converts the electrical energy to acoustic energy, and vice versa. The active element is basically a piece of polarized material with electrodes attached to two of its opposite faces. When an electric field is applied across the material, as shown in **Figure. 2.11**, the polarized molecules will align themselves with the electric field, resulting in induced dipoles within the molecular or crystal structure of the material. This alignment of molecules will cause the material to change dimensions. This phenomenon is known as electrostriction. A permanently-polarized material such as quartz ( $\text{SiO}_2$ ) or barium titanate ( $\text{BaTiO}_3$ ) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force. This phenomenon is known as the piezoelectric effect.



**Figure 2.11: Piezoelectric Crystal with Current Off and On [3]**

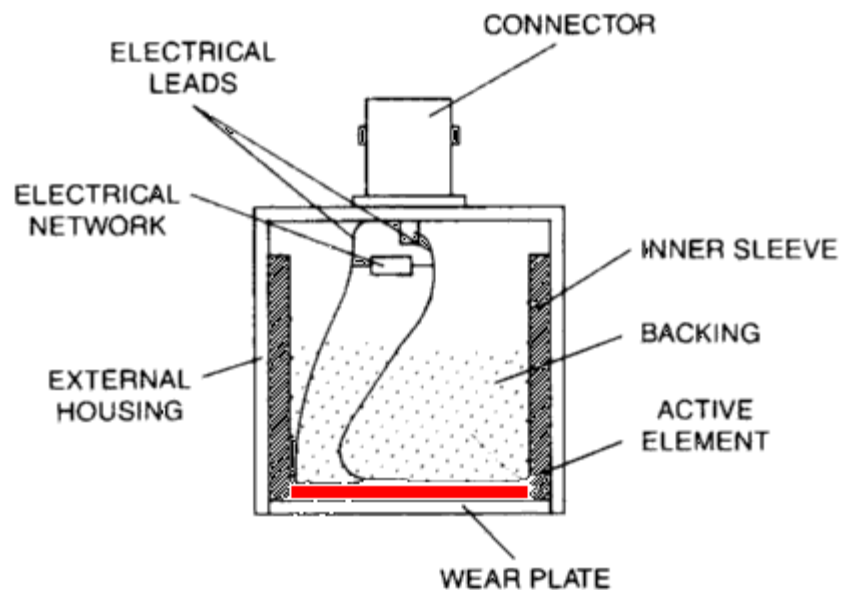
Main components of Transducer/Probe head as shown in **Fig 2.12** are,

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

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

### 2.6.1 Components of Transducer

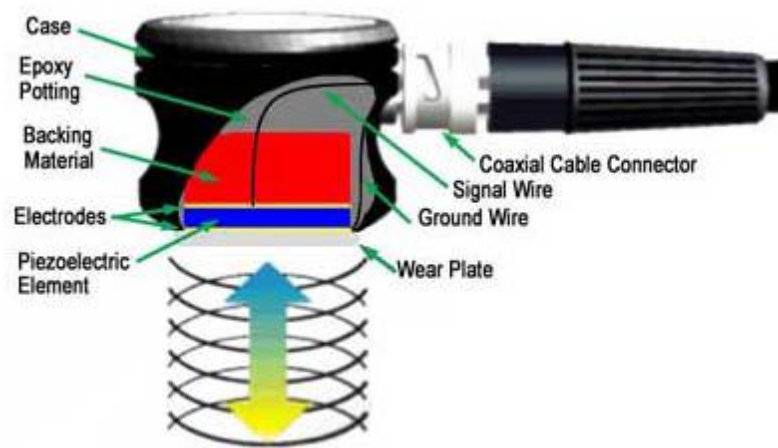
As shown in the **Fig. 2.12**, the components of the transducer and their functions are as follows. The main purpose of the wear plate is simply to protect the piezoelectric transducer element from the environment. Wear plates are selected to generally protect against wear and corrosion. In an immersion-type transducer, the wear plate also serves as an acoustic transformer between the piezoelectric transducer element and water, wedge or delay line.



**Figure 2.12: Piezoelectric Transducer [9]**

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

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

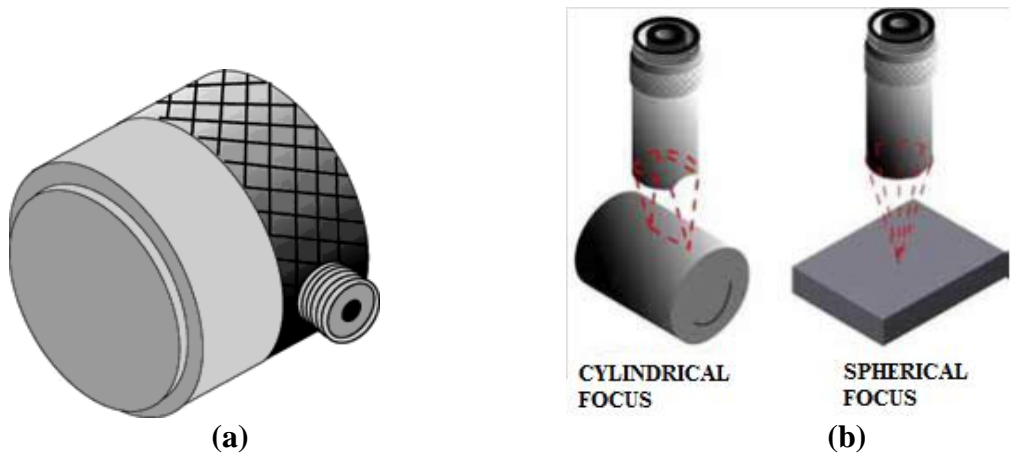


**Figure 2.13 Components of Transducer [10]**

### 2.6.2 Types of Transducer

Transducers are classified into groups according to the application.

- **Contact transducers** are used for direct contact inspections, and are generally hand manipulated, as shown in **Figure. 2.14(a)**. They have elements protected in a rugged casing to withstand sliding contact with a variety of materials. These transducers have an ergonomic design so that they are easy to grip and move along a surface. They often have replaceable wear plates to lengthen their useful life. Coupling materials of water, grease, oils, or commercial materials are used to remove the air gap between the transducer and the component being inspected.



**Figure 2.14: (a) Contact Transducer, (b) Immersion Transducer [10]**

- **Immersion transducers** do not contact the component. These transducers are designed to operate in a liquid environment and all connections are watertight, as shown in **Fig. 2.14(b)**. Immersion transducers usually have an impedance matching layer that helps to get more sound energy into the water and, in turn, into the component being inspected. Immersion transducers can be purchased with a planer cylindrically focused or spherically focused lens. A focused transducer can improve the sensitivity and axial resolution by concentrating the sound energy to a smaller area. Immersion transducers are typically used inside a water tank or as part of a bubbler system in scanning applications.

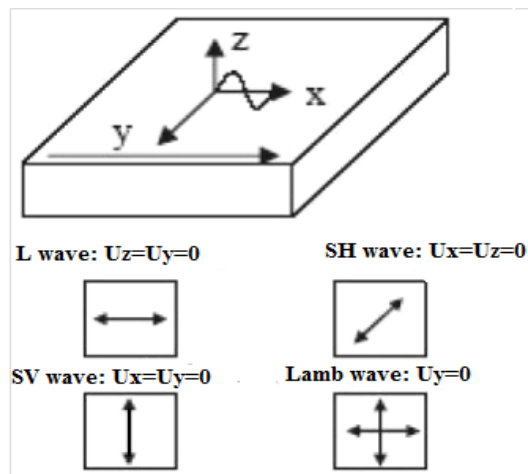
## 2.7 ULTRASONIC GUIDED WAVES IN PLATED STRUCTURES

Guided waves are waves whose propagation characters depend on structural geometries, such as plates, rods, pipes, etc. These waves are generated by impinging the plate obliquely with a piezoelectric transducer or by directly using transducer in contact with plate.

In plates these ultrasonic waves propagate in two ways:

- Longitudinal ultrasonic wave (L): displacement of particles is parallel with the energy transport direction.
- Shear ultrasonic wave (S): displacement occurs in the direction perpendicular to energy transport.

Shear wave, can further propagate in two modes (**Figure 2.15**).

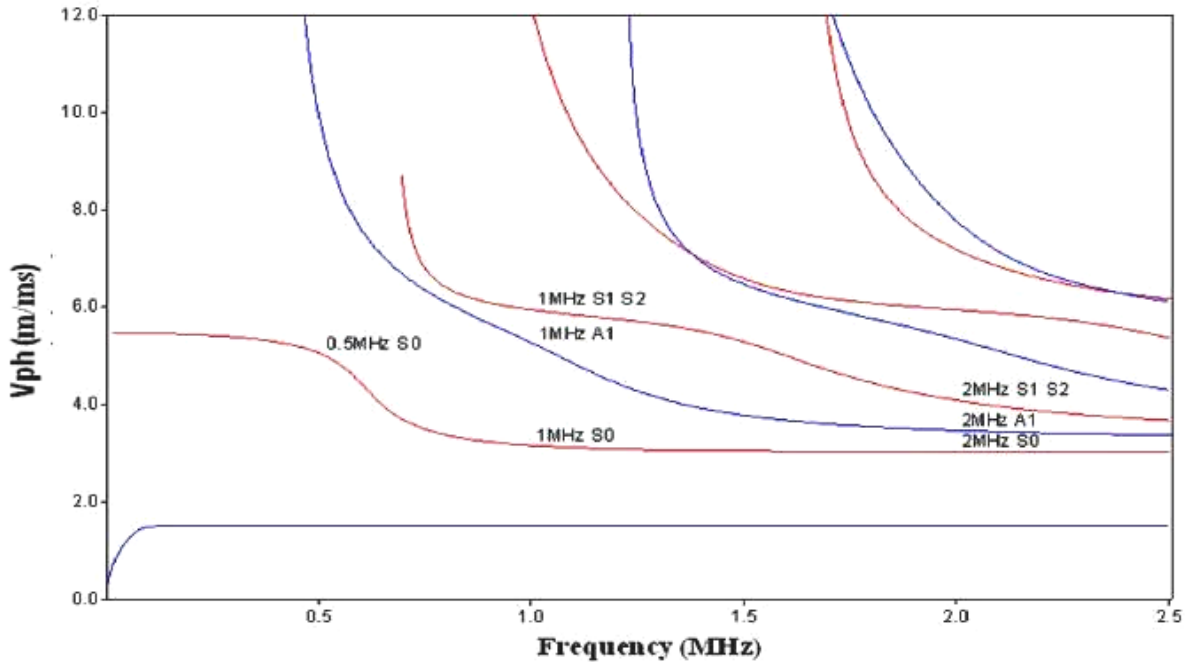


**Figure 2.15 Various Modes of Shear Waves [3]**

To use lamb waves for defect detection in plated structures, knowledge of the lamb modes is must for detecting the defects at specific depth.

## 2.8 DISPERSION EFFECT IN PLATES

This phenomenon of the wave speed dependence on the frequency is called dispersion phenomenon and these waves are called dispersive waves. The Lamb wave speed is not only dispersive but also multi-valued. At a given frequency multiple values of the wave speed are obtained for these waves. Different wave speeds correspond to different modes of the propagating Lamb wave. Such multiple modes do not exist for the longitudinal wave, shear wave.



**Figure 2.16 Dispersion curves for Lamb wave propagation in a 4 mm steel plate, immersed in water [11]**

For example, in the **Figure 2.16** , at the particular frequency e.g. 1MHz, the dispersion curve shows the existence of four modes (S0, A1, S1 and S2, where S1 and S2 are overlapped) propagating through the plate, of which S0, S1 and S2 are symmetric modes and A1 is anti symmetric mode. At the given frequency, the velocity of mode S0 is 3 km/s, mode S1-S2 is 6km/s and A1 is 5.5 km/s. The particular mode at 1MHz frequency can be obtained by varying the striking angle, calculated by Snell's law i.e. for S1 mode, the phase velocity is 6km/s, so the striking angle (A1) for S1 mode at 1MHz is calculated as follows by Snell's law:

Let the angle required is A1,

$$\frac{\sin A1}{C1} = \frac{\sin 90}{C2}$$

C1 is velocity of lamb wave in water (1.5 km/sec).

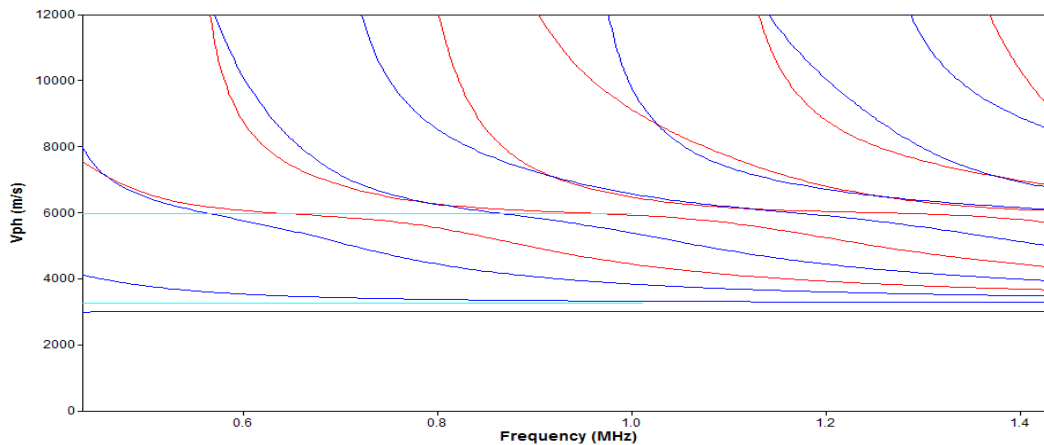
C2 is phase velocity of lamb wave in Steel (6 km/sec).

$$A1 = \sin^{-1} \frac{C1}{C2}$$

$$A1 = \sin^{-1} \frac{1.5}{6}$$

$$A1=14.7^{\circ}$$

So at an angle of  $14.7^{\circ}$  (of both transmitter and receiver) at 1MHz, we get  $S_1$  mode. The dispersion curves of Lamb wave modes could be obtained by solving wave equation with boundary conditions. In case of ultrasonic testing in air the transducer is in contact with the specimen along with the couplant but it is touched in perpendicular direction to the surface to be tested. So in this case it becomes difficult to identify the mode of the ultrasonic wave. By determining speed of a particular mode from the DISPERSE software we can roughly estimate mode at a given time for a given frequency. So dispersion curves are important tool for estimating various characteristics and modes of given ultrasonic wave.



**Figure 2.17: Dispersion curves for Lamb wave propagation in a 4 mm steel plate, in air**

## 2.9 CLOSURE

In this chapter, general principle of ultrasonic testing is discussed. A brief description of modes of propagation of ultrasonic waves had been discussed. Various methods of ultrasonic testing, types of transducers and components of transducers have been discussed. Criteria of dispersion of waves in plated geometries are also discussed in detail.

## CHAPTER 3

### LITERATURE REVIEW

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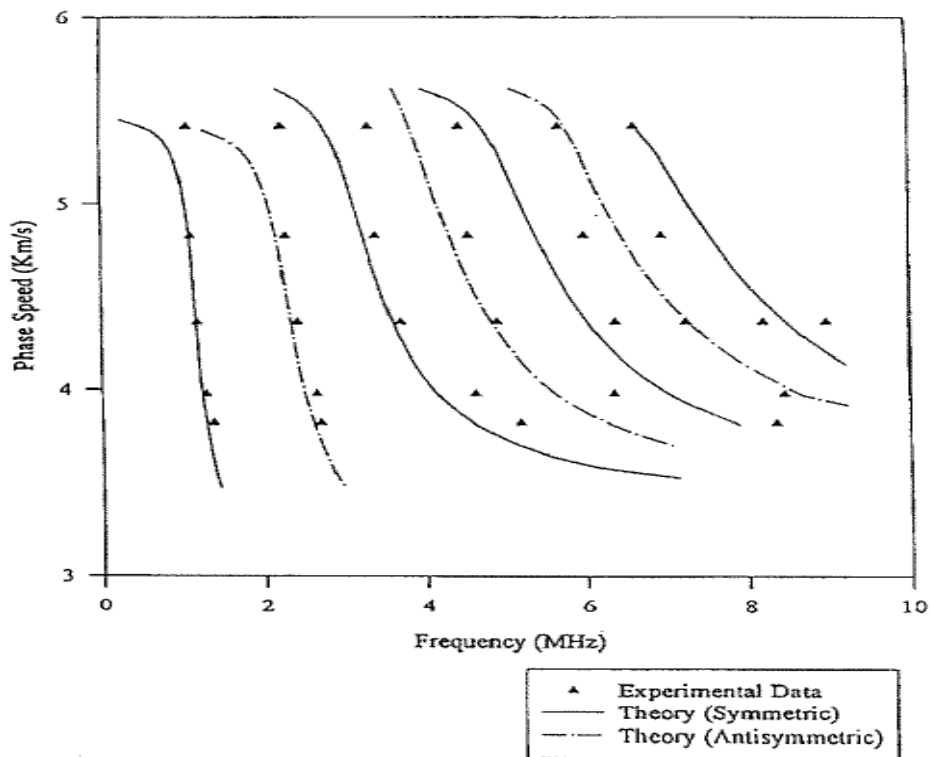
#### 3.1 GENERAL

Ultrasonic is a very efficient way of detecting defects in NDT. So these can be very efficiently used to detect defects in plated structures. This chapter presents a review of literature on utilization of ultrasonic guided waves for damage detection in plated structures. This gives an idea of study carried out in this area up to this stage.

**Alleyne[12]** discussed the problem associated with measurement of lamb waves. The key problem was that invariably more than one mode was excited at any given frequency. A new method was presented for measuring the amplitudes and velocities of lamb waves. This involved a 2-dimensional fourier transformation (FFT) of the time history of the signals received at a series of equally spaced positions along the propagation path. The output of this transform was a 3-dimensional plot of the amplitude versus frequency and wave number from which the amplitude of the different propagating lamb modes may be obtained. Further the numerical predictions of lamb wave reflection from boundaries and interaction with straight sided notches were presented and numerical model was validated by experimental investigations carried out on a variety of plates with straight sided notches.

**Kundu et al. [13]** discussed methods of detecting kissing bond in the plate structure was discussed. When the crack surfaces stay in very close contact with each other then the bond between the two surfaces of the crack is called a 'kissing bond'. When the crack surfaces are smooth then kissing bonds cannot transmit shear stress very well but can carry compressive normal stress, these bonds are called 'slip bonds'. These bonds remain invisible to the conventional P-wave based C-scan or A-scan techniques. In this paper it was shown that the kissing bonds can be effectively detected by some leaky Lamb mode. Theoretical and experimental results were presented to show that using the Lamb waves is an effective way of detecting kissing bonds. Conventional ultrasonic techniques could detect internal cracks and inclusion type defects in homogeneous as well as layered materials. But the conventional ultrasonic scanning was not very efficient for detecting cracks which are located normal to the specimen surface. Back scattering technique and acoustic microscopy technique can detect such

vertical cracks when they are located near the specimen surface. However, these techniques failed when the cracks were not very close to the surface.



**Figure 3.1: Comparison of theoretically calculated and experimentally observed Lamb wave dispersion curves for double layered specimen.**

**Ghosh et al. [14]** investigated the wave propagation in large plates and its use in internal defect detection had been studied. Both symmetric and anti symmetric modes had maximum flow rate at the central plane of the plate. Energy approach is efficient for vertical defects but its not efficient in case of horizontal defects. So for this it was important to compute stress distribution inside the plate. If a particular component of stress was affected by a defect then the lamb wave sensitive to that defect was required. Internal variation of other stress components which are not affected by defect were not of interest since both defective and non defective specimen would produce same levels for those stress components. The experimental values of  $V(f)$  curve are plotted on theoretical dispersion curve. Comparison between specimen with defect and without defect was compared and percentage change in the mode signal was found at the point of defect. Finally they found that lamb waves were more sensitive to the horizontal defects. Different modes were affected differently by the same defects.

**Rose et al. [15]** In order to establish a technical concept for the detection of defects in thin steel plates, an experimental investigation was carried out for the artificial defects in 2.4mm thick steel plates by using guided wave technique. The goal was to find the most efficient testing parameters paying attention to the relationship between the excitation frequency by tone burst system and various incident angles. For the case of  $S_0$  mode impingement, amplitudes of reflected signals were proportional to sizes of defects.  $A_0$  mode was also sensitive to the same defects but proportional relation was not observed. Tone burst signals were used to control the center frequency and frequency bandwidth of excited signals. The dispersion curves of Lamb wave modes could be obtained by solving wave equation with boundary conditions. In this case, the phase velocity was continuously controlled by variable angle shoe so that the phased velocity tuning could be performed by incident angle tuning.

**Shin and Song [16]** Lamb wave mode conversions were experimentally studied to utilize the mode conversion characteristics for the nondestructive testing. Aluminum plates with various depths of EDM notches were used for the experiments. The numerical results of Lamb wave dispersion in the plate were given. Short time Fourier transforms was employed to obtain the dispersive patterns of the group velocity of the received signals, which represented experimental results of Lamb wave dispersion. Then, the mode identifications were performed by the comparison of the dispersive patterns obtained by numerically and experimentally. For the excitation and reception of the Lamb waves, angle beam transducers with tone burst signals were used. Mode conversion was observed in both pitch-catch and pulse-echo techniques. Mode conversions occurred in forms of phased velocity shift and frequency shift. It showed the possibility of defect detection by using Lamb wave pitch-catch techniques. In addition, by analyzing the characteristics of mode conversion, it might have been possible to size defects with Lamb waves.

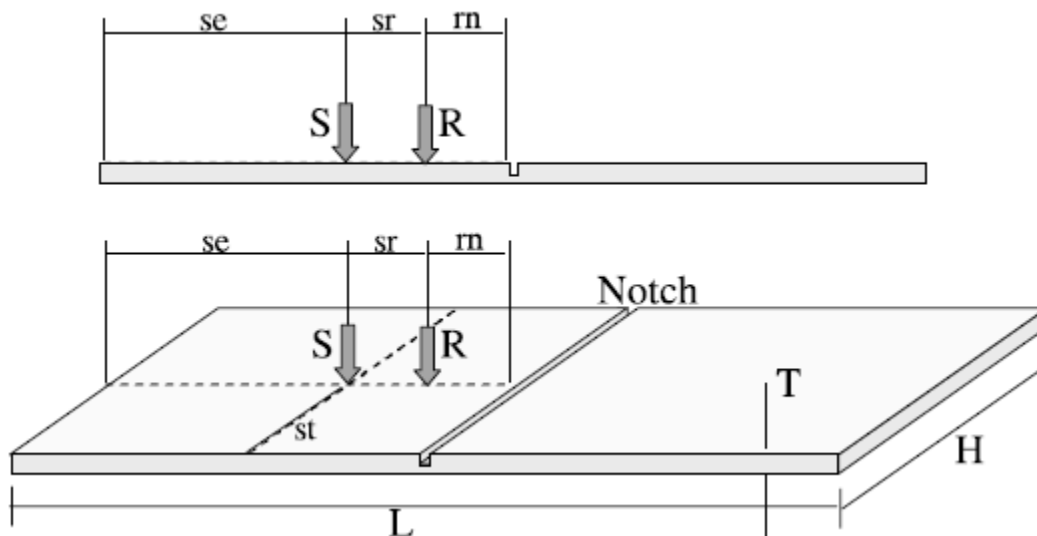
**Younho [17]** In this paper, utilization of hybrid boundary element modeling for specific Lamb wave mode incidence situations with special energy distributions along the structural cross section was proposed for estimating reflection and transmission from various scatterers, such as a step discontinuity and tapered parts of a waveguide, etc. Interaction of individual Lamb wave modes with scatterers that represent arbitrary thickness variation along the direction of guided wave propagation was investigated by calculating the scattered fields for varying incident modes, frequency, and scatterer shape. The mode conversion phenomenon through step discontinuity in

a plate was also experimentally explored. The theoretical predictions of reflection and transmission by boundary element methods and the utility of dispersion curves were compared with experiments for specific modes. Results in this paper could be used to improve inspection sensitivity and penetration power for a variety of practical NDE applications, notably those in which thickness variation was found. In addition, the feasibility of inspecting sections located behind a waveguide thickness variation region and subsequent mode control was also been discussed. The integrated approach including hybrid BEM simulations for physically based data on the guided wave mode conversion phenomenon and corresponding experiments with redundancy based on the appropriate angle tuning and self calibration could help to extract rich features from the guided wave mode conversion phenomenon for more optimized and quantitative guided wave applications.

**Fromme [18]** the scattering of the first anti symmetric Lamb wave mode  $A_0$  at obstacles in plate-like structures was studied in this dissertation. The propagation in an isotropic, homogeneous plate, the scattering at a circular hole, and the scattering at a hole with a defect were investigated experimentally and theoretically. Guided flexural waves had the advantage of propagating over large distances in plates, thus allowing the fast and efficient detection of defects in large structures. This method holds promise for the nondestructive testing of aircraft Airplane fuselage and wings often consist of aluminum face sheets, connected with fasteners or containing holes, which are sources of stress concentration and crack formation at their boundaries. When the guided wave hits such a discontinuity, a typical scattered displacement field is obtained. A change in the scattered field indicates the development of a fatigue crack, and thus the growth of such cracks can be monitored. In the experiments, the  $A_0$  mode was excited selectively by means of a piezoelectric transducer with a well-defined time signal. The used frequency range was below the cut-off frequencies of the higher wave modes in the plate. The scattered field was measured on a grid around the hole with a heterodyne laser-interferometer Using fast Fourier transformation, the amplitude and phase values of the scattered field were extracted from the measured time series. The introduction of a small imperfection, like a notch, at the boundary of the cavity changed the measured scattered field significantly. The first anti symmetric Lamb wave mode  $A_0$  physically represented a flexural wave propagating along the structure. It can be described well using approximate theories. Therefore no three-dimensional theory needed to be implemented, and a fast calculation was achieved. Good agreement between

the experimental data and the analytical solutions was found for the extent of validity of the different models. A stable and fast numerical calculation of the scattered field around the hole and notch is achieved.

**Valle and Littles Jr[19]** The current study presented an effective alternative procedure by combining a novel digital signal processing technique, the reassigned spectrogram, with laser generated and detected Lamb waves to detect flaws in the metallic plates. The reassigned spectrogram was used to characterize the modal and frequency content of a single ultrasonic signal as a function of time, enabling a procedure to locate flaws in an aluminum plate specimen. The problem of locating flaws in thin metallic parts (such as an aluminum plate) were of tremendous importance, due to an increasing tendency to maintain aging structures in service much beyond their originally designed service life. The principal obstacle to a robust, rapid and accurate localization technique based on broadband multi-mode guided waves was dispersion, as dispersion could alter the incident signal more than the potential flaws. The objective of the present study was to demonstrate the accuracy of using laser-generated and detected Lamb waves that were operated on by the reassigned spectrogram to locate notches in a metal plate.



**Figure 3.2: Schematic of specimen used for experimental measurements. The distances from source to receiver (sr), receiver to notch (rn), source to edge (se), and source to top (st) are also indicated.**

These flaws were located with multi-mode, dispersive Lamb waves by combining broadband laser-generation techniques with high fidelity laser-detection (this combination was capable of tracking the dispersive nature of this problem), and operated on these signals with the reassigned

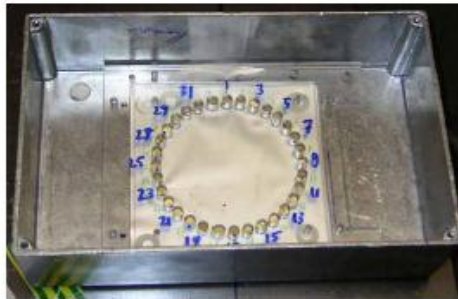
spectrogram. Most importantly, the present work established the necessary requirements of using the reassigned spectrogram to operate on field measured signals and thus located flaws in metallic waveguides, even when the acoustic characteristics (dispersion curves) of the perfect (unflawed) waveguide were not available—this was generally the case in field situations. The reassigned spectrogram had been shown to be capable of accurately capturing many Lamb modes, which had undergone severe dispersion, in perfect (unflawed) aluminum plates. This study used a similar technique to accurately locate notches of various depths by superimposing the analytical dispersion curves (transcribed first in the time–frequency domain) onto the reassigned spectrogram of the time-domain signals. Flaws were detected by analyzing every part of the reassigned spectrogram that did not fall onto the dispersion curves, as a reflection due to either the notch or the boundaries of the plate.

**Demma[20]** In this thesis the author investigated the effect of geometrical discontinuities in plates and pipes on the propagation of guided waves. The discontinuities studied are both defects in the structure and features of the structure. Firstly the scattering of the SH0 mode from discontinuities in the geometry of a plate were presented. Both Finite Element and modal decomposition methods have been used to study the reflection and transmission characteristics from a thickness step in a plate, very good agreement being obtained. A method to approximate the reflection from rectangular notches by superimposing the reflection from a step down (start of the notch) and a step up (end of the notch) was proposed. The limits of this method in approximating crack-like defects were discussed. The second part of this thesis reports an experimental and numerical (Finite Element method) study of the reflection of the T(0,1) mode from defects in pipes. Both crack-like defects with zero axial extent and notches with varying axial extents were considered in this study. An interpretation of the crack-like reflection coefficients in terms of the wave number-defect size product was proposed.

**Diligent[21]** In this thesis inspection of plates was done using lamb waves. The inspection of a plate by Lamb waves required the propagation of multiple signals in order to achieve full coverage. This was achieved using a plate tester device which had been developed separately. The work presented in this thesis investigated the interaction of the fundamental Lamb modes with a free edge of a plate and with different types of defects with very simple geometries. This is studied in order to bring understanding of the detection capabilities of the inspection system, as well as to aid the signal

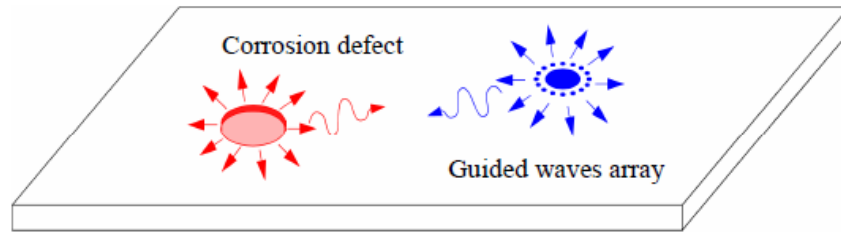
processing procedures used by the system. The reflection of Lamb waves when the fundamental anti symmetric Lamb mode ( $A_0$ ) or the fundamental symmetric Lamb mode ( $S_0$ ) was incident at the free end of a plate was studied, in order to identify the extent to which the generation of non-propagating modes influenced the field local to the end of the plate. The results of this work are important if the plate tester device was placed close to a defect, or close to the edge of a plate, because the non-propagating modes could then interfere with propagating modes and pollute the signal processing. A second and more complex case was above this cut-off frequency when there was more than one anti-symmetric mode. These two cases showed that there was some additional motion due to the non-propagating modes. It was also shown, in contrast, that no such additional motion happens in the case when the fundamental symmetric mode  $S_0$  was incident at the end of the plate.

**Fromme et al.[22]** In this paper the method of detecting defects in steel plate was discussed. Fromme et al. designed a guided wave array consisting of a ring of 32 piezoelectric transducer elements, equally spaced on a diameter of 70 mm. Each transducer element consisted of a PZT disc (diameter 5 mm, thickness 2 mm) and a backing mass. The array was permanently bonded to the structure using conductive epoxy glue. The individual transducer elements had been optimized to act as a good approximation to point sources and receivers for the transmission and reception of the first anti symmetric Lamb wave mode  $A_0$ .



**Figure 3.3: Array prototype**

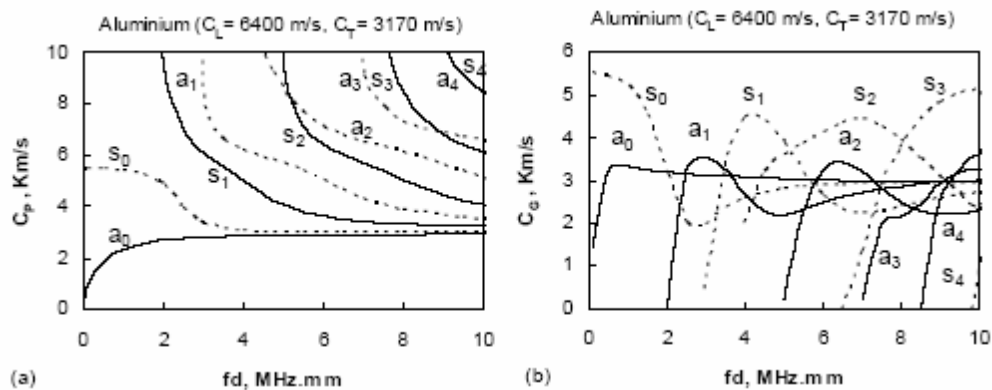
The circular array design was introduced to achieve the same performance in all directions. In order to ascertain the sensitivity of the array monitoring measurements, the predicted and measured reflection amplitude of the various structural features and defects was compared. On comparing the observed amplitudes of the reflections at the plate edges to the theoretical predictions good agreement had been observed.



**Figure 3.4: Schematic of guided ultrasonic wave monitoring of large plate like structures**

The measured reflections at model defects like circular through holes were compared to theoretical predictions and good agreement was found. Therefore an approximate indication of the severity of a defect could be obtained from the amplitude of the reflected signal. Defects simulating typical thickness reductions due to corrosion were machined into the plate. Good agreement between the measured reflections at circular flat bottom holes and Finite Element predictions was found. Simulated corrosion pitting and a rough ground defect could be well detected within the dynamic range of the array measurement.

**Edalati et al.[23]** In the present study, the numerical method was investigated for drawing the dispersion and displacement curves of ultrasonic lamb wave, propagated in Aluminum thin plate. It was found that amplitude analysis can give some qualitative information about defects depth by using Distance-Amplitude-Correction curves, but it was not sometime repeatable. In this respect, pulse echo method showed better sensitivity of amplitude to defects depth variation. It was found that these techniques could detect all fabricated defects. Pulse echo was more sensitive for defect detection than emission technique. Location of defects was found by assessment the group velocity in pulse echo technique.



**Figure 3.5 a) phase and b) group velocity dispersion curves, propagated in Aluminium plates.**

The effect of thickness, frequency and different modes of lamb wave on the phase and group velocity was defined in dispersion curves. It was seen that some modes were sensitive to coating or surface defects and some modes were sensitive to internal defects.

**Oppenheim et al.[24]** In this paper the authors examined the detection of fatigue cracks in a specimen that exhibited the complications of multiple welded joints. They induced a fatigue crack in a particular location and recorded Lamb wave reflections during the development of the fatigue crack and also later after mechanical enlargement of the fatigue crack. In this paper we explore the detection of crack generation and growth using Lamb wave transducers was explored. Two wired transducers were located on each side of the girder. In principle one could detect a crack by using a single transducer as both an emitter and a receiver, or alternatively by using a transducer pair in a pitch-catch configuration. However, in this experimental work use of additional transducers to obtain insight into the robustness of the crack detection was done. The transducers were near to but not extremely close to the anticipated crack location, making crack detection more challenging. It would be necessary to distinguish crack-induced reflections from other reflections from the various joints and the flange and stiffener ends. The enlarged cracks were clearly apparent from the reflected Lamb waves while the smaller fatigue-induced cracks were not unambiguously detected. These results were robust with respect to changes in the pulse center frequency and also were clearly observed for all transducer pairs.

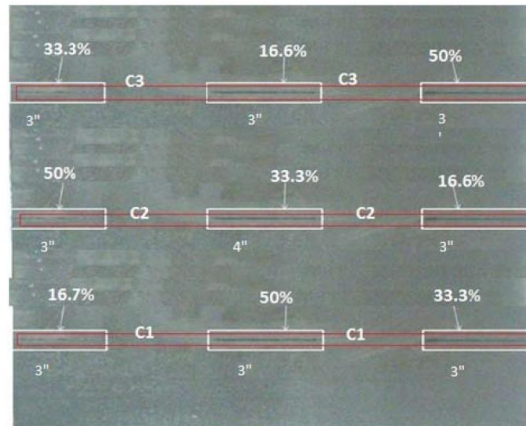
**Fromme[25]** The first part of this presentation had introduced to the concept of distributed sensors for the monitoring of large plate structures employing the first antisymmetric Lamb wave mode A0. The sensitivity for the detection and localization of defects was discussed and the influence of the number of sensors and evaluation algorithm was studied. Good results had been found for defects in plates and the measurements were validated by a comparison to synthetic data from Finite Element simulations using ABAQUS Explicit. In the second part the application of guided ultrasonic waves for the in-situ monitoring of fatigue crack growth at fastener holes, a common problem in aircraft maintenance, was demonstrated. In laboratory experiments on tensile aluminium specimens, good results and repeatability were achieved using low frequency guided waves and laser interferometry measurements. In order to improve the sensitivity for the

detection of small fatigue cracks, the usage of Rayleigh-like waves was investigated. In the frequency-thickness range of interest Rayleigh-like waves in plates, which could be interpreted as the superposition of the fundamental Lamb modes A<sub>0</sub> and S<sub>0</sub>, transfer energy between both surfaces with a characteristic distance called the beat length. A simple analytical model and Finite Difference (FD) calculations were used to describe the reflection of the Rayleigh-like wave at small surface defects. Experimentally the Rayleigh-like waves can be excited using standard wedge transducers and measured using either standard pulse-echo equipment or laser interferometry. Good sensitivity for the detection of small defects on both plate surfaces had been found. Full three-dimensional simulation of the scattering of the Rayleigh wave at the fastener hole and crack has been implemented using the FD method. The comparison of the results showed a good correlation to the observed signals.

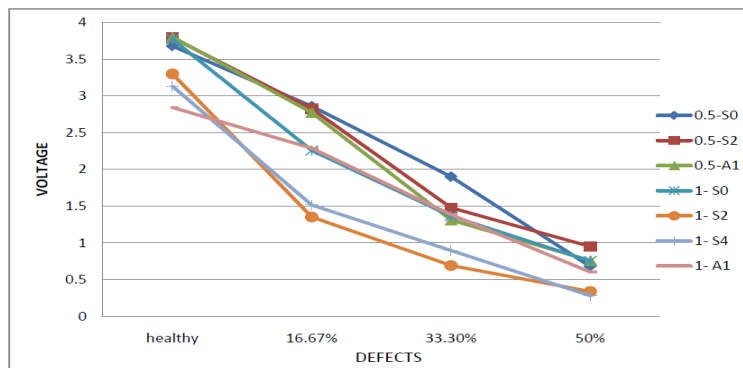
**Srivastava[26]** This dissertation presented the use of ultrasonic guided waves for the structural health monitoring of plates, rods, and waveguides with complex cross-sections like multilayered composite laminates, 7-wire steel strands, and rails. Modeling of guided waves by a Semi Analytical Finite Element (SAFE) model was presented. This model assumed constant cross-section along the direction of propagation. Therefore, while SAFE can efficiently compute dispersion characteristics of complicated waveguides, it cannot be used to study scattering due to local irregularities. A Global Local (GL) model, which combined SAFE and FE, was presented. This model was used to study scattering and mode-conversion effects of local defects in Aluminum plates and composite laminates. It has been shown that the nonlinear features of guided waves were often more sensitive to small defects than the linear features. This included generation laws for plate and rod modes at nonlinear higher harmonics which underline the analogous behavior of nonlinear bulk waves and nonlinear waves in plates and rods. Finally, SAFE simulations of nonlinear waves in rail were presented.

**Singh[3]** presented the use of ultrasonic technique to detect the damage in steel plates, submerged in water, with seeded defects in the form of notches, considering the inherent irregularities in the plate specimen. Pulse transmission technique and the pulse echo method were used for detection of the seeded defects in the plates. Negative spike pulse was used as an input signal to sending transducer through Pulser/Receiver system and transmitted pulse was received at the other end by receiving transducer. Ultrasonic waves were introduced at different

angles to excite the different modes in the subject specimen in both pulse echo and through transmission technique. The signals thus obtained were digitized using digitizer card. Before scanning a plate seeded with defects, specimen plate was tested in healthy condition, for inherent irregularities in it. Ultrasonic testing was done at different stages of defects. These inherent irregularities could lead to misinformation regarding the presence, extent and location of the defect. So a correction factor had been formulated to nullify the effect of the inherent irregularities present.



**Figure 3.6: 6mm steel plate, showing the depth and location of defects**



**Figure 3.7: Trends of various modes for Notch defects in 6mm plate**

The combination of pulse echo and pulse transmission readings had been successfully used to generate the tomograms of the specimen plate. Application of the correction factor on the readings obtained had been found to significantly improve the tomograms regarding the extent and location of the defect.

**Shelke et al.[27]** studied detection of ultrasonic guided waves for delamination was studied in laminated aluminum plates. For this purpose a broadband piezoelectric transducer structured with a rigid electrode was used. Appropriate excitation frequencies and modes for inspection were selected from theoretical and experimental dispersion curves. Sensitivity of antisymmetric

and symmetric modes for delamination detection were investigated. The antisymmetric mode was found to be more reliable for delamination detection. Unlike other studies, in which the attenuation of the propagating waves is related to the extent of the internal damage, in this investigation, the changes in the time-of-flight (TOF) of guided Lamb waves were related to the damage progression. The mode conversion phenomenon of Lamb waves during progressive delamination was investigated. Close matching between the theoretical and experimentally derived dispersion curves and TOF assures the reliability of the results presented here. Two broadband piezoelectric transducers were attached on two sides of the aluminum plate for generation and detection of Lamb waves.

At higher frequencies, symmetric modes S2 and S0 showed change in TOF with delamination, but the degree of change in the spectrogram shape with delamination is found to be much stronger for the anti symmetric mode; therefore this mode is recommended for delamination monitoring in the laminated plate.

### **3.2 CLOSURE**

The chapter reviews the work done in the field of defect detection in plates using ultrasonic testing techniques. Different type of defects to be detected and techniques that are implemented in this field are discussed in this chapter. As ultrasonic testing is a vast field with its wide spread applications so there are still many areas where this technique can be effectively implemented.

## DAMAGE DETECTION IN PLATES – SIMULATED STUDIES

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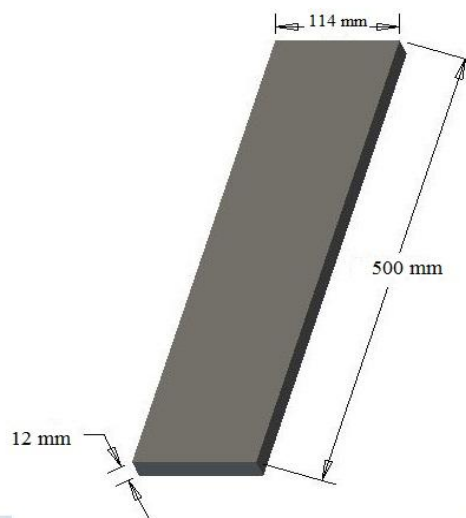
### 4.1 INTRODUCTION

Damage detection has been an important area of concern in the design, operation, maintenance and repair of many military, industrial and civil structures and equipment involving plate structures, submerged in water or in air. In this chapter the feasibility of using guided waves for damage detection in plates with simulated notch defects is explored.

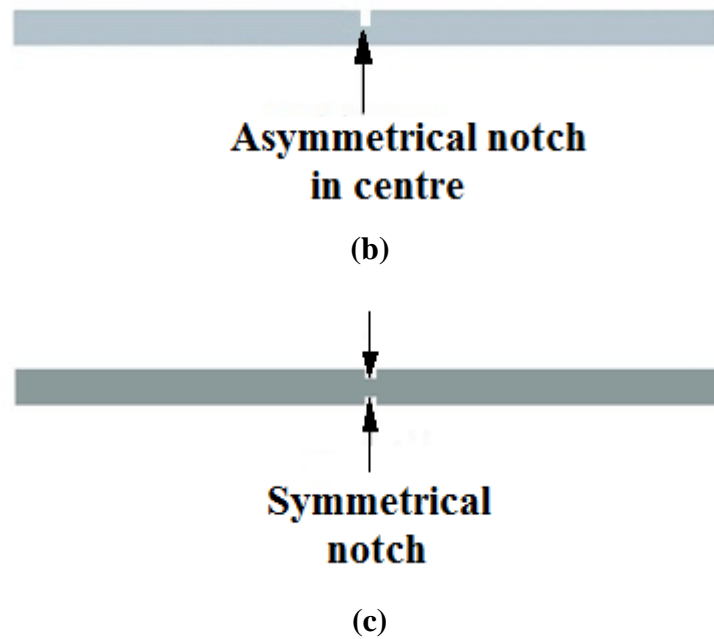
### 4.2 EXPERIMENTAL STUDY

#### 4.2.1 Specimen Details

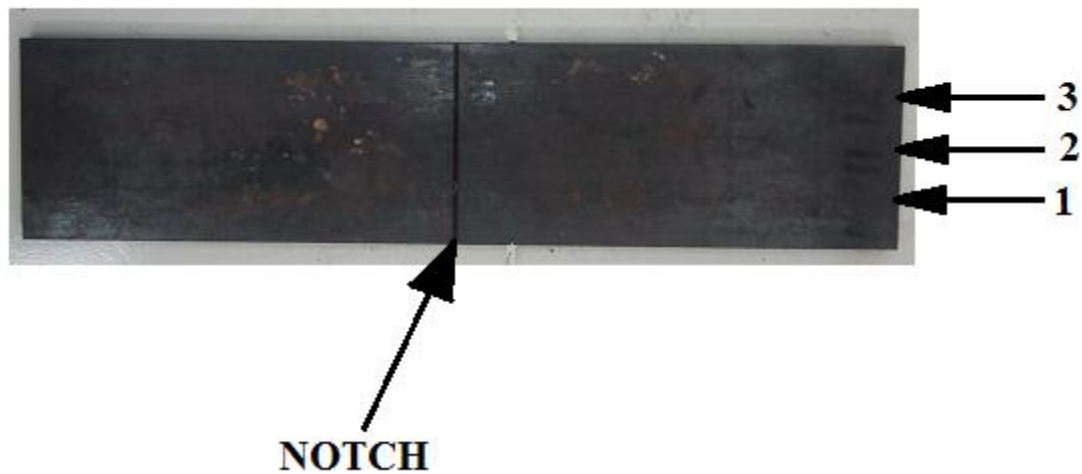
For damage detection study in plates, mild steel plates of the dimension  $500\text{mm} \times 114\text{mm} \times 12\text{mm}$  as shown in **figure 4.1 (a)** were fabricated. Two types of specimens with simulated notches were made as shown in **figure 4.1 (b), (c)**. On one plate notch was made one side of the plate (i.e. asymmetrical notch). The depth of notch was incremented by 1mm and the ultrasonic testing was done at each stage till the notch was 9mm deep. On the next plate notch was made symmetrically on both sides of the plate with the initial depth of notch made was 0.5mm and the ultrasonic testing was done at each state till the notch was 4.5mm deep on each side of the plate. Readings were taken on three different locations as shown in **figure 4.2** on the plate for the repeatability of the experiment.



(a)



**Figure 4.1: (a) healthy plate; (b) plate with one sided notch; (c) plate with symmetrical notch**

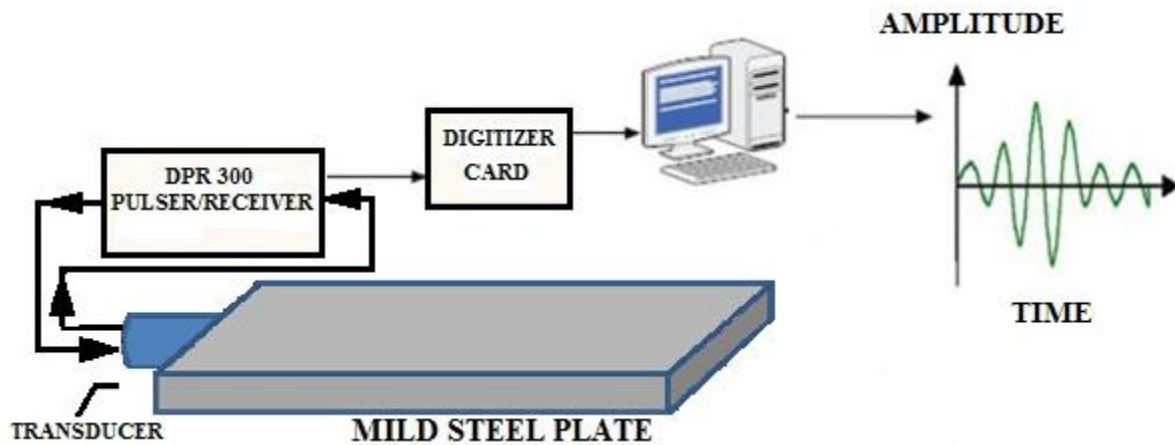


**Figure 4.2 Three testing locations**

#### **4.2.2 Setup**

The experimental setup consisting of a typical ultrasonic system, pulser/receiver which generates the pulse for every given time interval. The pulse generated has been sent to the transducer which transfers the pulse to an ultrasonic wave. Transmitter transducer has been in contact with the plate through the couplant and the other end the receiver transducer has been also arranged in the same way (pulse through) or the reflected wave from the other

end is received by the same transducer acting as transmitter (pulse echo). This transducer has been connected back to the pulser/receiver, sends the signals to the digitizer card which has been connected to computer hardware. Driven by the pulser/receiver, the compressional transducer generates ultrasonic pulse that propagates through the plate in the form of longitudinal waves as shown in **figure 4.3**. When there is an interface such as a crack, void or flaw in the wave path, part of the energy is reflected back from the interface and received by the same transmitting transducer. The reflected energy has been converted into an electrical signal which has been processed in a computer and digitized for display. Pulse echo and through transmission methods are used for characterizing the damage. The presence of the defect and extent of damage can be ascertained by through transmission. However pulse- echo method has been used to locate the defect and also to ascertain the extent of damage. Transducers having longer wave form duration and a relatively narrow frequency bandwidth with centre frequency of 2MHz, 1MHz and 0.5MHz has been used for the 12mm thick plate specimens.



**Figure 4.3: Experimental setup with digitizer card used for capturing the wave signatures**

**Following are the salient features of the equipments used:**

**Transducer**

A contact transducer is a single element longitudinal wave transducer intended for use in direct contact with a test piece. It can be used in straight beam flaw detection and thickness gauging, detection and sizing of delamination, material characterization and sound velocity

measurements, inspection of plates, billets, bars, forgings castings, extrusions, and a wide variety of other metallic and non-metallic components. **Figure 4.4.**

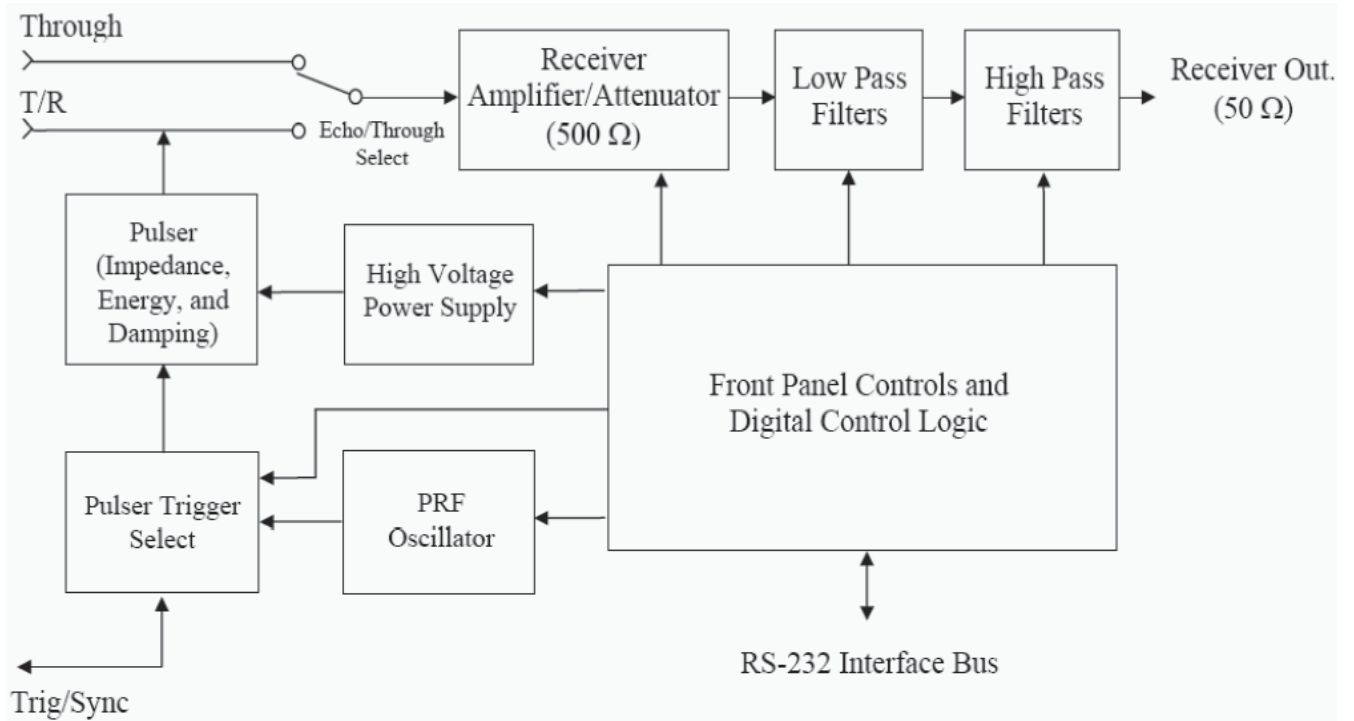


**Figure 4.4: Transducers of 1 MHz, 2 MHz and 0.5 MHz**

#### **JSR Ultrasonic DPR 300Pulser/ Receiver System**

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

With the DPR300 configured for pulse-echo mode operation, acoustic echoes reflected from interfaces or defects within the test material are converted by the transducer into electrical signals that are presented to the T/R connector of the DPR300. The low-noise DPR300 receiver amplifies these electrical signals, and the signals then pass through adjustable high pass and low pass filters. The DPR300 receiver gain is adjustable between -13 dB and 66 dB, and there are six high pass and six low pass filter settings for band-limiting the receiver frequency response. The amplified and filtered signals are available on the instrument's Receiver Output connector. The DPR300 may also be used in transmission mode operation wherein a separate receiving transducer is used to detect acoustic pulses that have propagated through a test material or medium. Detailed circuit diagram of pulser/receiver is given in **figure 4.5.**



**Figure 4.5: Detailed circuit diagram of Pulsar/Receiver system**

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

**Pulsar (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. **Table 4.1** shows configuration of pulse generator used.

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

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

**Table 4.1: Configuration of JSR Pulse Generator**

| <b>Pulser</b>                  |  |
|--------------------------------|--|
| 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 $\mu$ Joules minimum, 304 $\mu$ Joules maximum for 475V pulsers. Dependent upon energy and voltage setting                |
| Pulse Duration                 | Typically 10-70 ns FWHM for 50 $\Omega$ 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 ohm.                                 |
| 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. External: 0 - 5 kHz for 475V pulsers.   |
| Sync Output                    | Maximum +5 V, $t_r < 30$ ns, $t_w = 50$ ns. min.<br>TTL and CMOS compatible. Minimum value of load impedance is 50 ohm.        |
| 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 |

| <b>Receiver</b>  |  |
|------------------|--|
| Gain             | -13 to 66 dB in 1 dB steps controlled by the host computer                   |
| Phase            | 0degree (no inverting)   |
| Input Impedance  | 500 ohm(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 $\mu$ V pk-pk input referred(measured at 60dB,35 MHz bandwidth) |
| Output Impedance | 50 ohm   |
| Output Voltage   | $\pm$ 0.5 V into 50 ohm  |

### **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** shows the configuration of digitizer card

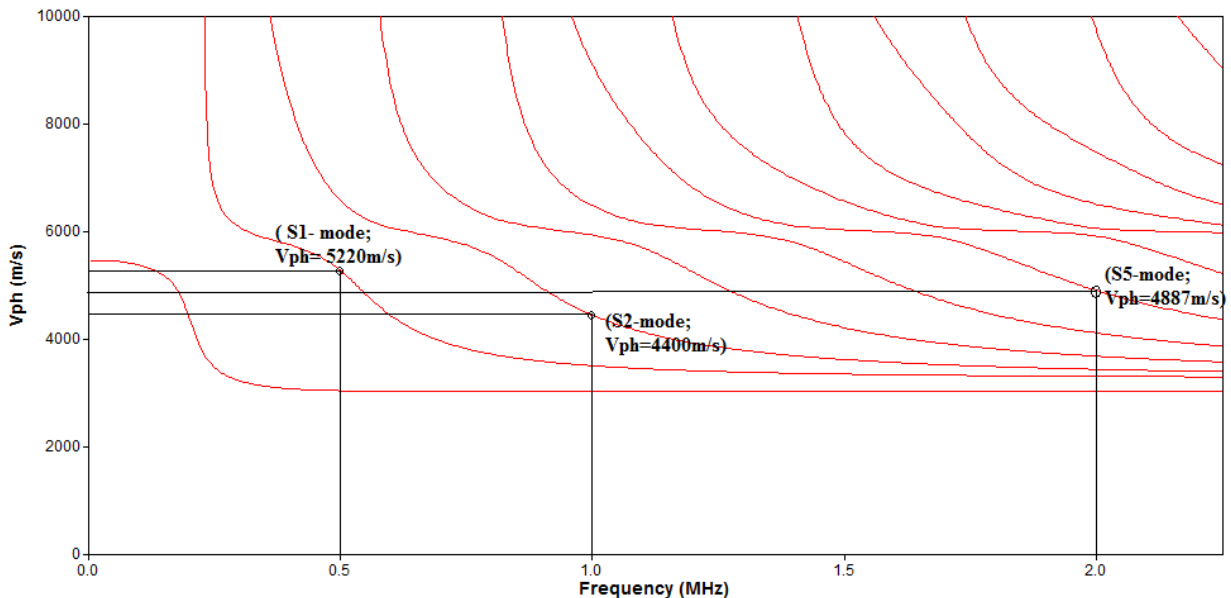
**Table 4.2 Configuration of Digitizer Card**

| <b>Model DC438</b>     |   |
|------------------------|---|
| 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 ohm $\pm$ 1% @ DC                      |
| Connector              | BNC, gold-plated                          |
| Channels               | Two                                       |
| Coupling               | DC  |
| Maximum Input Voltage  | $\pm$ 10 V DC (2 W) or 10 V RMS at 50 ohm |
| Bandwidth Limit Filter | 35 MHz 2-pole Bessel filter (DC438)       |
| Minimum Amplitude      | 1 V pk-pk                                 |
| Impedance              | 50 ohm                                    |

### 4.2.3 Selection of optimum frequency and Mode

Transducers with center frequencies of 0.5 MHz, 1 MHz, and 2 MHz were used during the study. These transducers correspond to good signal fidelities. The transducers were driven by a Pulsar/receiver system with maximum gain of 66 dB and maximum input voltage of 475V. An external PC and Digitizer card was used to capture the received signal and for further processing. The transducer was mounted in a holder and coupled using an industrial coupling gel. The excitation signal consisted of a negative spike pulse with pulse duration ranging from 10-70 ns.

The results illustrate that different frequencies and modes have different dispersion characteristics with a trend toward higher frequencies having slower energy transport velocities. While testing in air it is difficult to separate different modes for excitation. A rough idea of mode obtained at a particular time can be obtained from dispersion curves which can be modeled in DISPERSE software **figure 4.6**. From the dispersion curves we can determine the velocity of particular mode for a given frequency of excitation. So knowing the distance and time we can calculate velocity at a particular point and compare it with theoretical velocities of different modes obtained from dispersion curve and roughly estimate which mode is obtained at a given point of interest.



**Figure 4.6: Dispersion curves for Lamb wave propagation in a 12 mm steel plate, in air.**

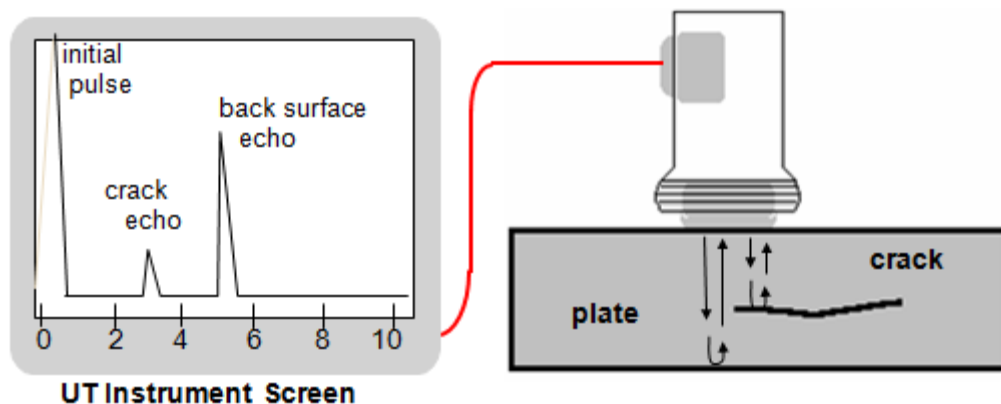
From the dispersion curve as shown in figure 4.6, for 0.5MHz phase velocity ( $V_{ph}$ ) of 5220m/s corresponding to  $S_1$  mode was excited in the plate. Similarly, for 1MHz  $V_{ph}$  of 4400m/s corresponding to  $S_2$  was found to be suitable for excitation. For 2MHz  $V_{ph}$  of 4887m/s corresponding to  $S_5$  mode was suitable for excitation. As the transducer of 1MHz will produce frequency near to 1MHz but it is not possible to obtain exact value of 1MHz. So the actual phase velocity is near to theoretical phase velocity which may not be exact value of it. Similar is the case for all the transducers.

#### 4.2.4 Ultrasonic Investigations- Simulated damage in plate

To simulate damage area reduction was done by increasing the depth of notch at the same location along the length of the plate. The Pulse echo method was used for characterizing the damage. The depth of the crack is the measurement of the transit time of the wave diffracted by the tip of the crack. Longitudinal wave was generated by placing the transducers normal to the cross section of the plate as shown in **Figure 4.8**. The nature of these waves is dispersive meaning that their propagation shall lead to generation of multiple modes at a given frequency.

#### Pulse Echo Testing

In nondestructive testing of metals, the ultrasonic pulse-echo (PE) technique has proven to be a reliable method for locating cracks and other internal defects. An electro-mechanical transducer is used to generate a short pulse of ultrasonic stress waves that propagates into the object being inspected as shown in **figure 4.8**. Reflection of the stress pulse occurs at boundaries separating materials with different densities and elastic properties.



**Figure 4.7: wave propagation in plate and its signature**

The reflected pulse travels back to the transducer that also acts as a receiver. The received signal is displayed on an oscilloscope, and the round trip travel time of the pulse is measured electronically. By knowing the speed of the stress wave, the distance to the reflecting interface can be determined.

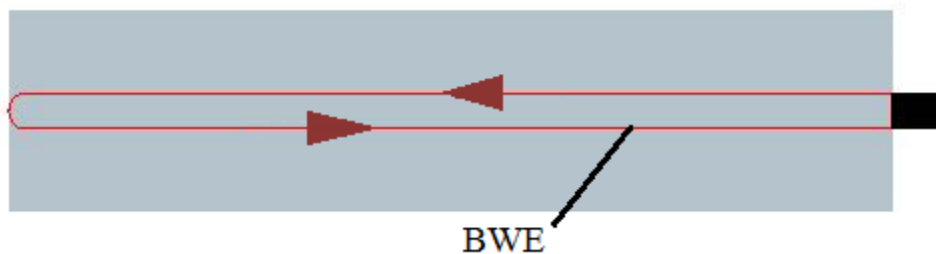
Time is known from time of flight (TOF) in signal. Phase velocity of the mode of excitation is known from the dispersion curve. So the location of the notch or crack can be obtained as;

$$D = \frac{v \times t}{2}$$

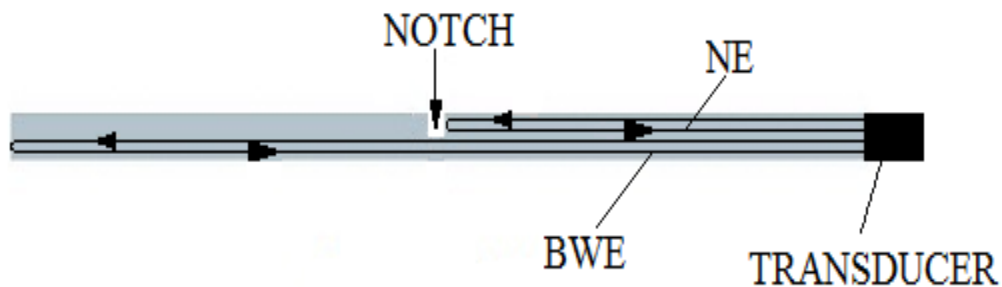
Where “v” is phase velocity of mode used,

“t” is time of flight,

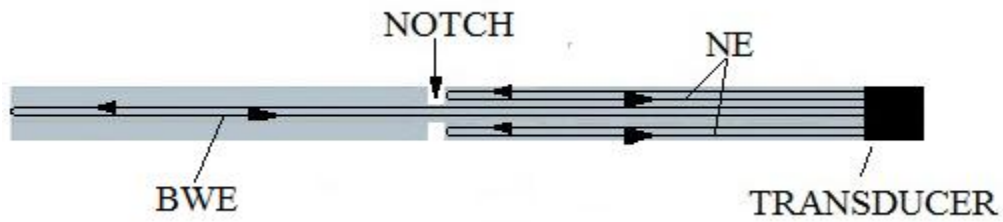
“D” is the location of interface from where an echo is obtained.



(a) Wave propagation in plate



(b) Wave propagation in Asymmetrical notch plate



(c) Wave propagation in Symmetrical notch plate

Figure 4.8: Pulse echo peaks

### 4.3 ULTRASONIC INVESTIGATION-RESULTS AND DISCUSSION

Location of damage i.e. notch was made at the length  $L/2$ . The Signals received from both the specimens were analyzed and compared with the healthy readings of that specimen. 0.5Mhz, 1Mhz, 2Mhz transducers were used. Readings were taken on three locations of the plate to demonstrate repeatability of the experiment as shown in figure 4.2.

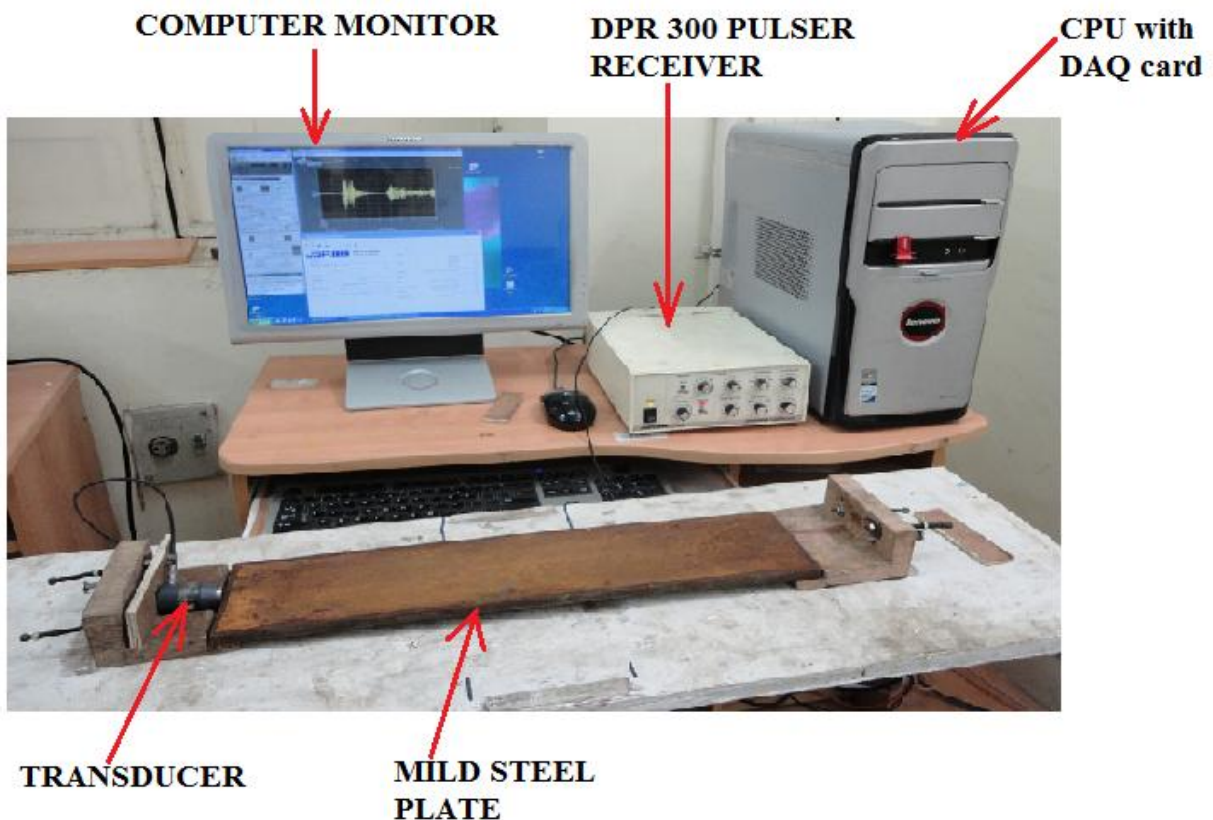


Figure 4.9: Setup for plate testing in air in Pulse Echo mode

### 4.3.1 Plate with Asymmetrical notch

#### 4.3.1.1 Results and Discussions

In this plate the notch was asymmetrical. The depth of notch was increased by 1mm each time after taking readings in PE mode at all the three frequencies. The notch was made on horizontal milling machine with HSS milling cutter of 2" diameter and 2mm thickness. Below are the signatures of all the transducers at three different locations and with different depths of notch made in the plates.

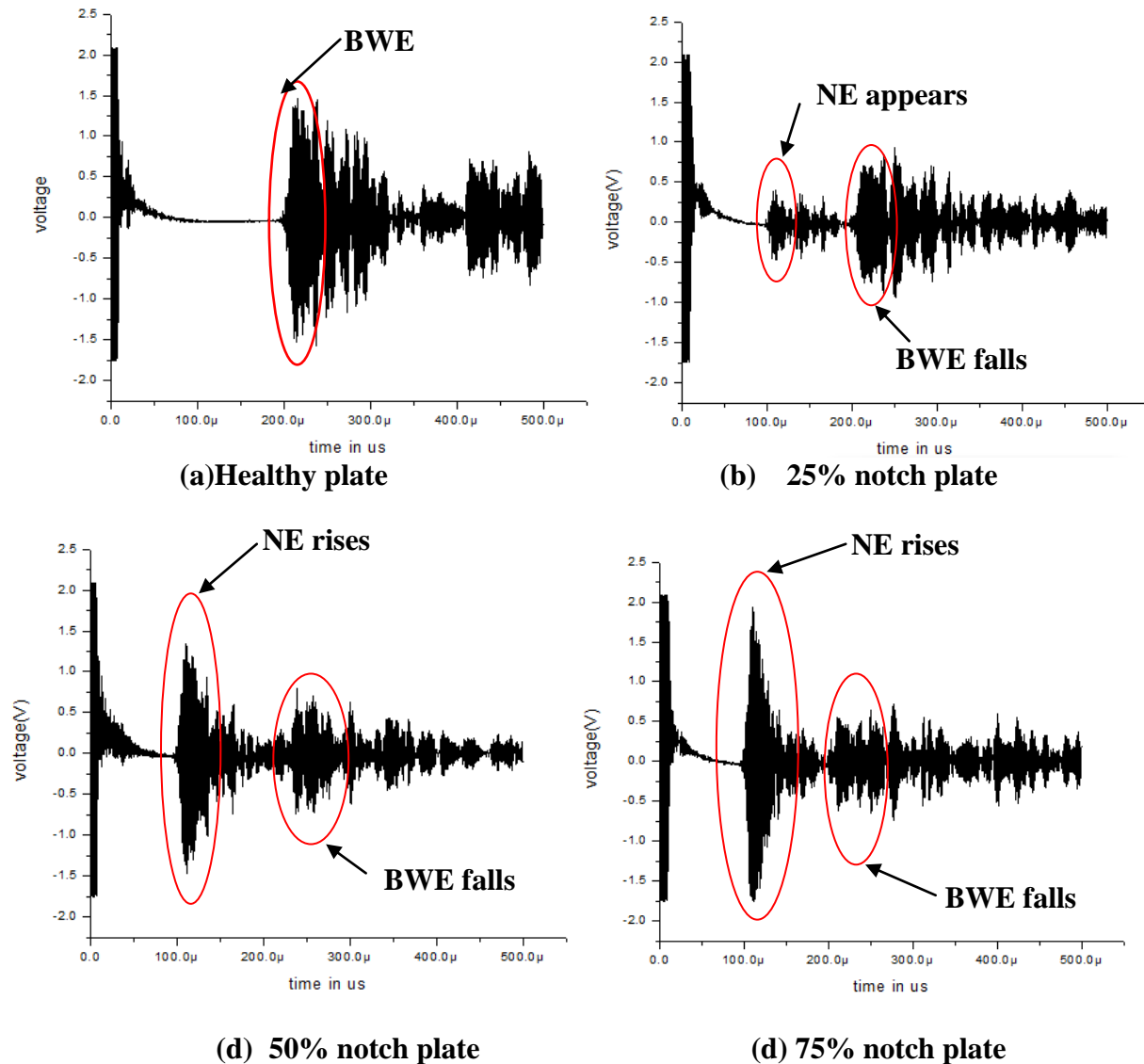


Figure 4.10: PE Signatures with 0.5MHz

Signatures of 1MHz transducer at various depths of notch are given below.

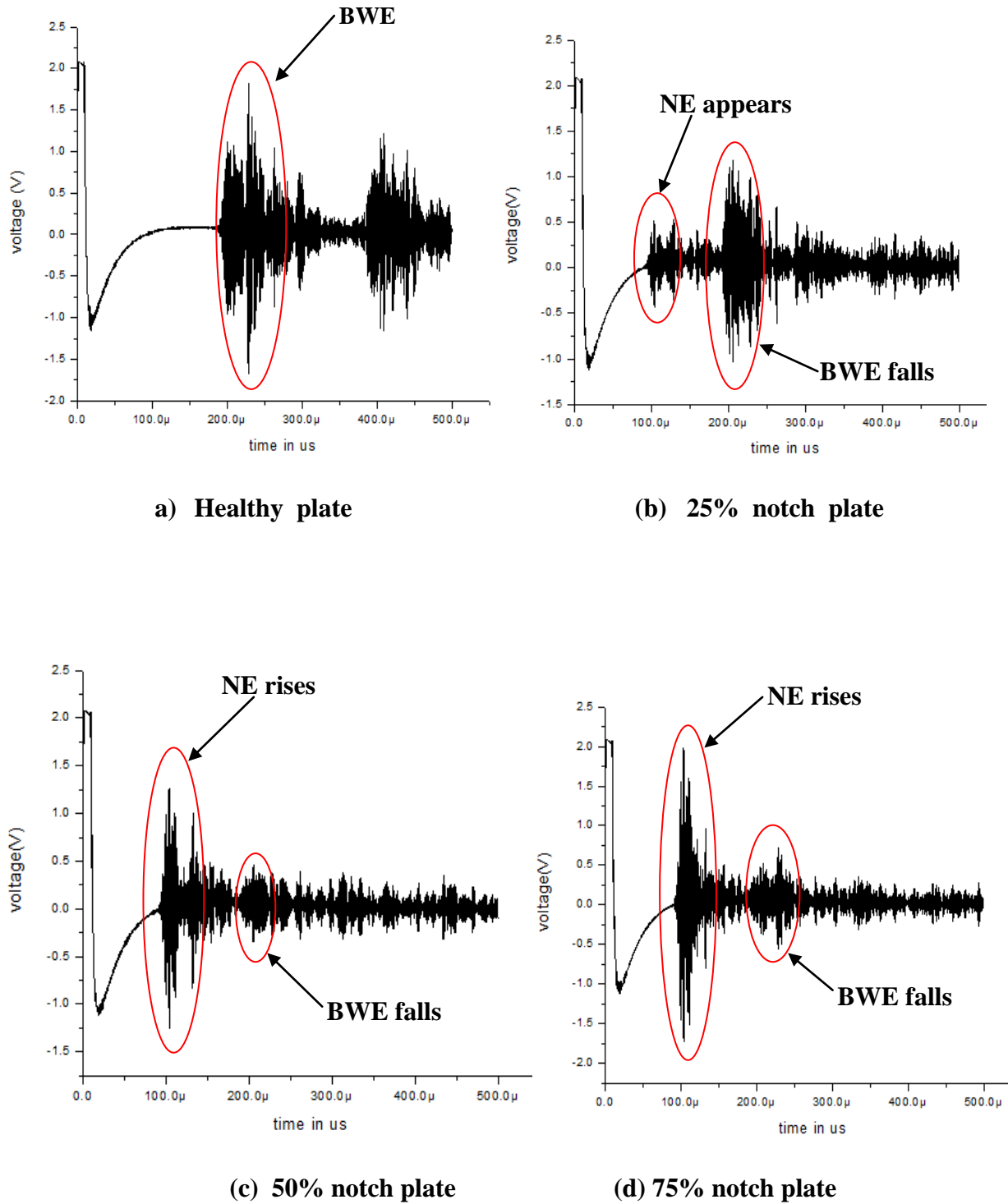
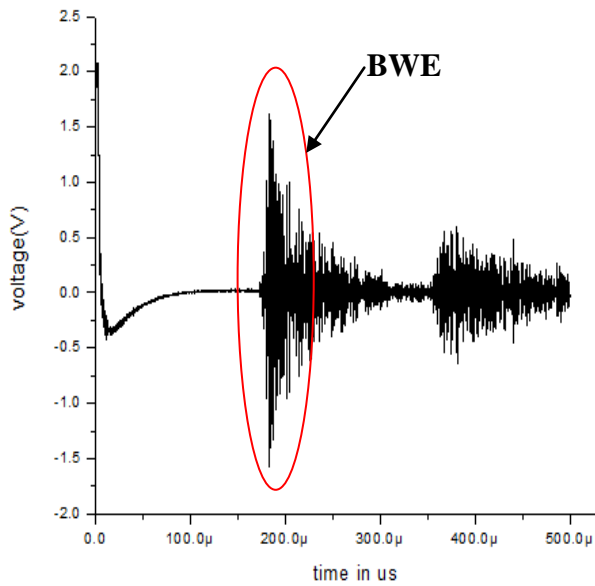
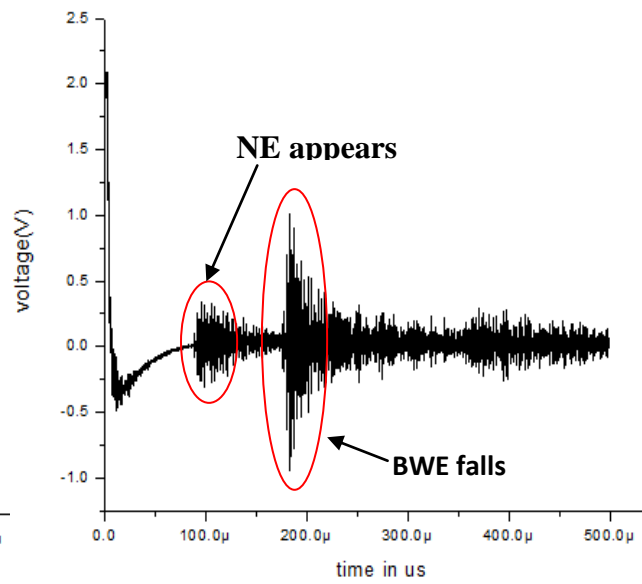


Figure 4.11: PE Signatures with 1MHz

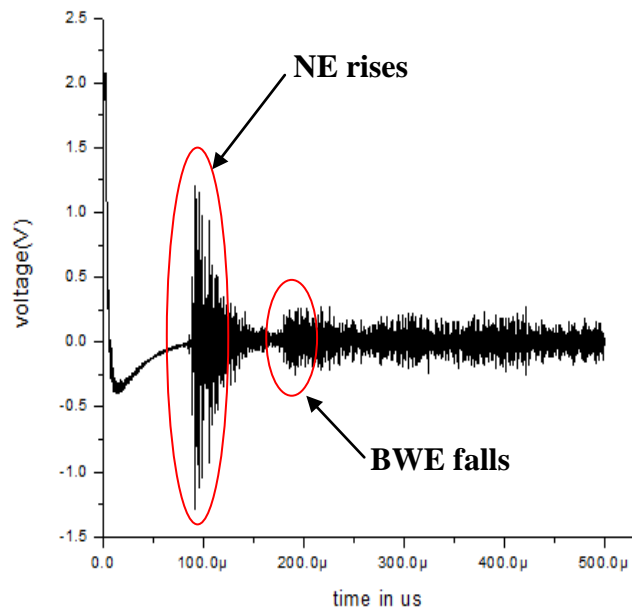
Signatures of 2MHz transducer at various depths of notch are given below.



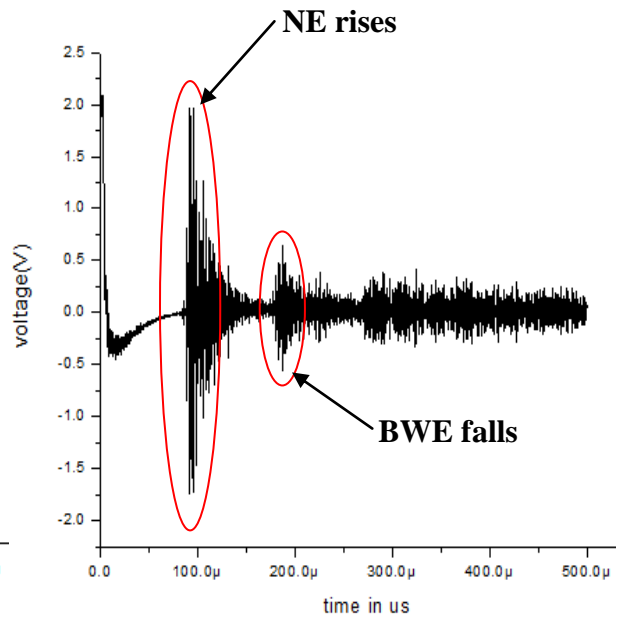
**a) Healthy plate**



**(b) 25% notch plate**



**(c) 50% notch plate**



**(d) 75% notch plate**

**Figure 4.12: PE Signatures with 2MHz**

From the signatures obtained in PE mode, following observations are made. Appearance of Notch Echo (NE) in notched plate as shown in **figure 4.11, 4.12, 4.13** as compared to healthy signatures of that plate as shown in figure indicates the presence of notch can be detected by all the three frequencies used.

- 1) Irrespective of frequency of excitation, as the depth of notch increases, BWE voltage amplitude drops and NE amplitude rises. This has been clearly depicted in the **figure 4.14, 4.15, 4.16**.
- 2) Location of damage can be determined. As we know in PE method  $D = \frac{v \times t}{2}$

Where, “v” is the velocity of particular mode,

“t” is the time of flight,

“D” is the length of plate in which wave is travelling.

From above three parameters “v” can be determined from dispersion curve for a particular mode and “t” can be determined from the given signature. So we can very easily estimate distance “D” from where the guided wave is reflected. So the defect can be located using above method of defect detection.

- 3) Magnitude of damage can also be determined in this technique. There are basically two ways in which magnitude of defect can be estimated. Firstly, as the depth of notch increases the BWE falls. Secondly, as the NE rises as the depth of notch increases. So the results can be further quantified to correlate depth of notch with the percentage rise of voltage in NE or percentage fall of voltage in BWE.

It was also observed that there was relatively very less drop in BWE for 0.5MHz frequency up to certain depth of notch. This is clearly depicted in **figure 4.13**. But 1MHz and 2MHz frequencies respond very well right from the initial start of the notch. This is due to the fact that 0.5MHz is a core seeking frequency while 1MHz and 2MHz are surface seeking frequencies. Moreover there is significant drop in BWE for 0.5MHz frequency as the depth of notch is increased from 33% of the total thickness.

Trends of fall voltage amplitude of back wall echo and rise in voltage amplitude of notch echo for all the three frequencies used is shown in plots below.

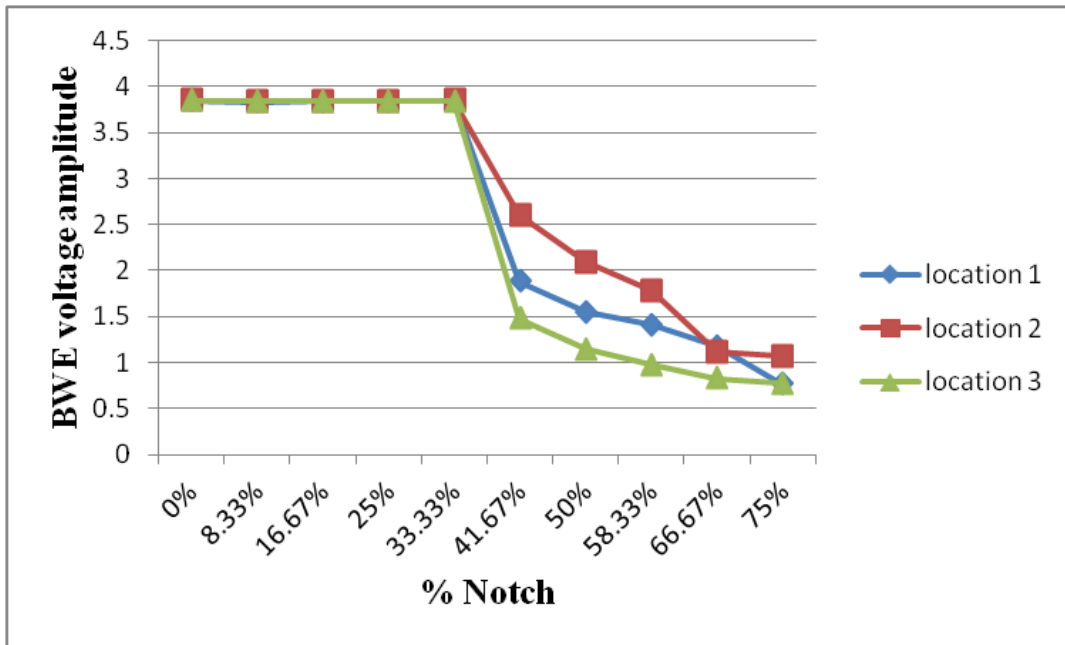


Figure 4.13: Voltage amplitude of BWE (0.5MHz)

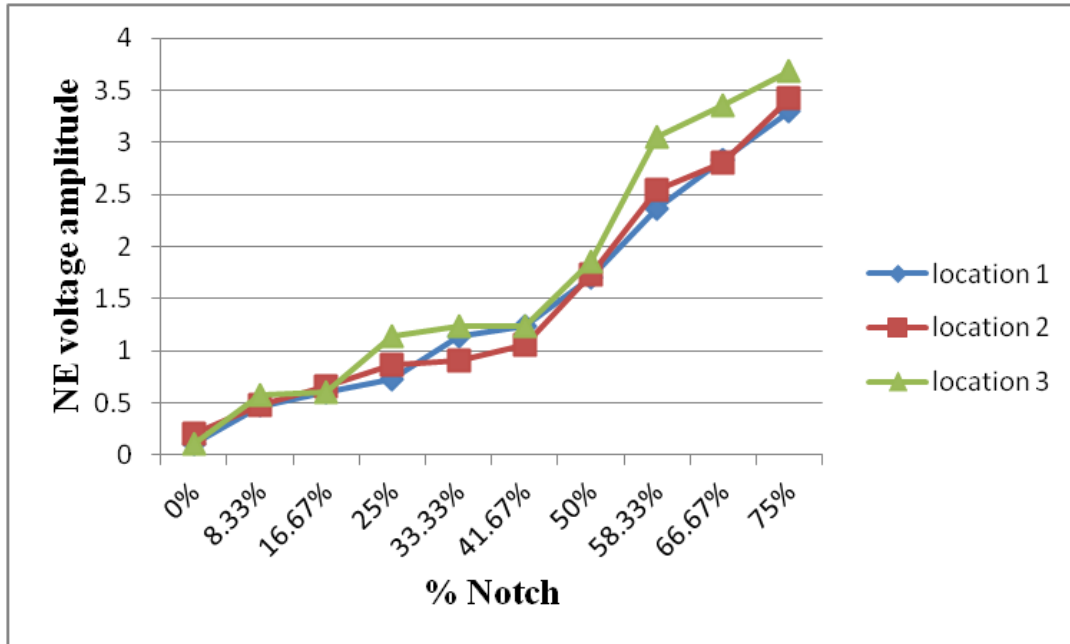
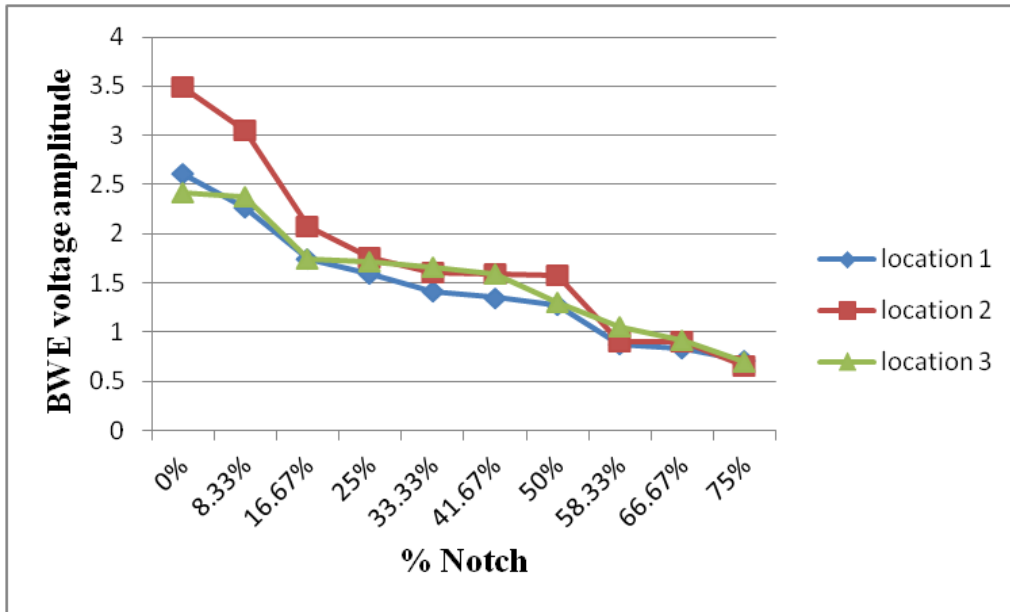
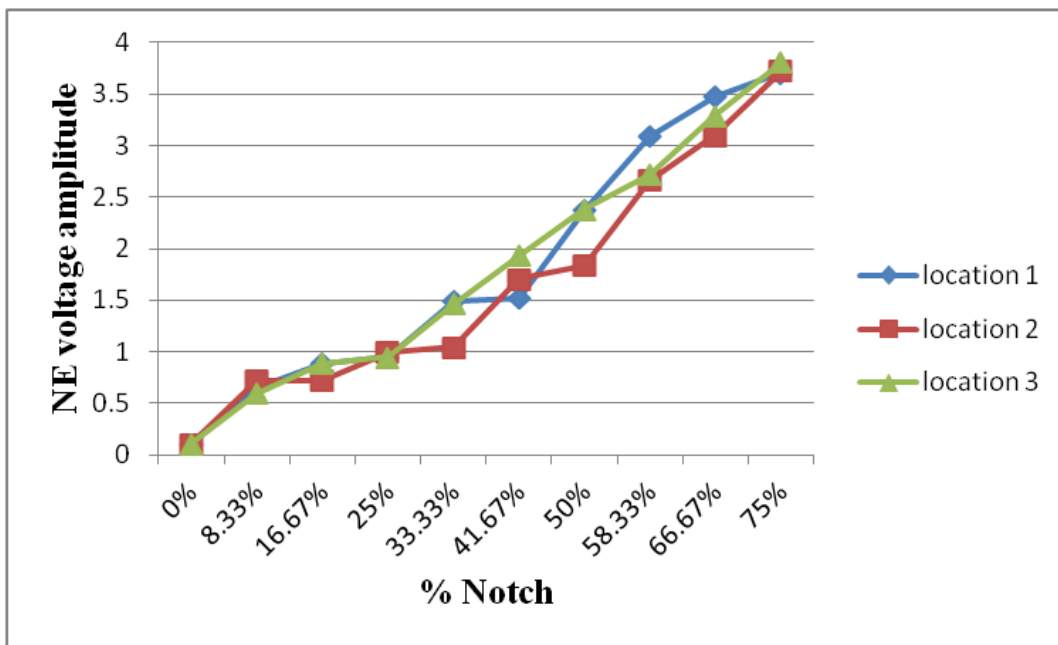


Figure 4.14 Voltage amplitude of NE (0.5MHz)

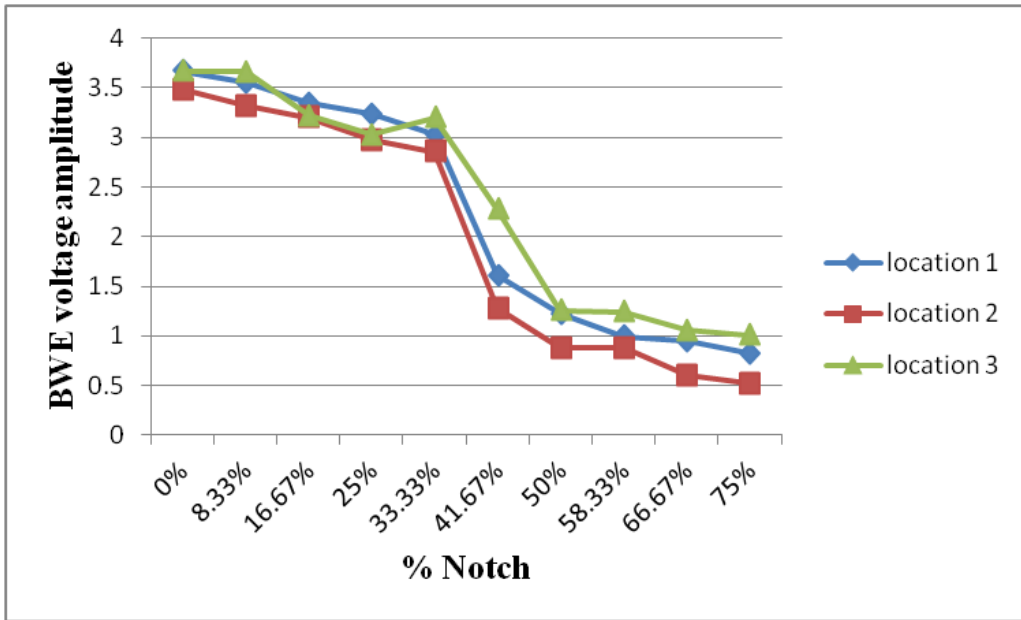


**Figure 4.15: Voltage amplitude of BWE (1MHz)**

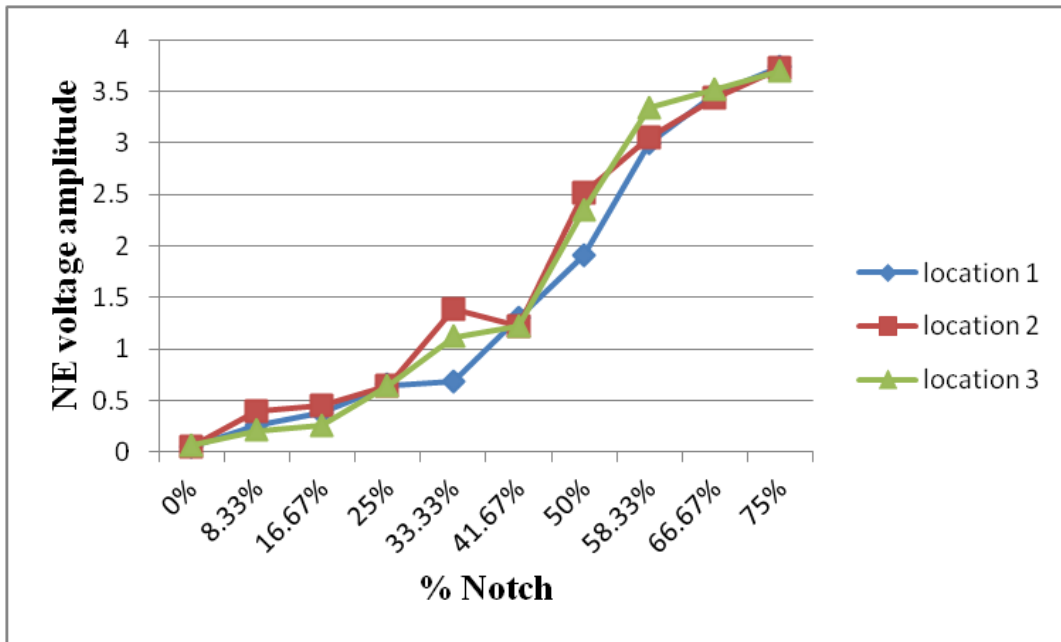


**Figure 4.16: Voltage amplitude of NE (1MHz)**

1MHz frequency is well suited for notch detection as there is almost regular trend of fall in BWE and rise in NE as in **figure 4.15, 4.16**. Moreover results are almost similar on all the three locations of testing. So this implies that the repeatability which is important for any experiment is possible in this case.



**Figure 4.17: Voltage amplitude of BWE (2MHz)**



**Figure 4.18: Voltage amplitude of NE (2MHz)**

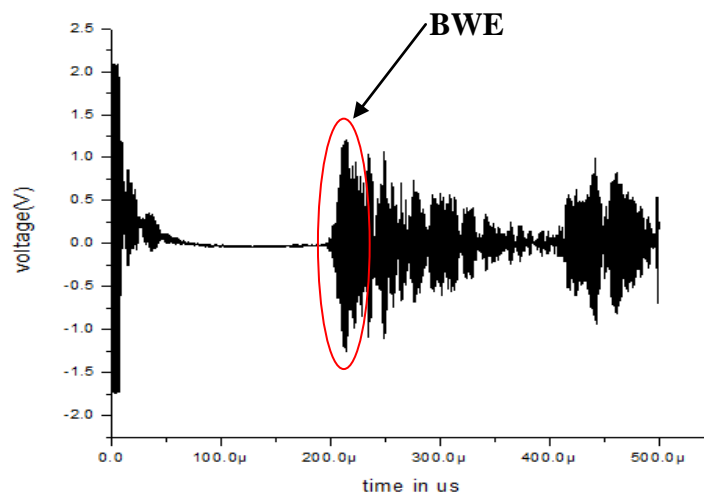
Similar to 1MHZ, 2MHz frequency also responds well for notch detection as there is almost regular trend of fall in BWE and rise in NE as in **figure 4.17, 4.18**. Moreover results are almost similar on all the three locations of testing. So this implies that the repeatability which is important for any experiment is possible in this case.

## 4.3.2 Plate with Symmetrical notch

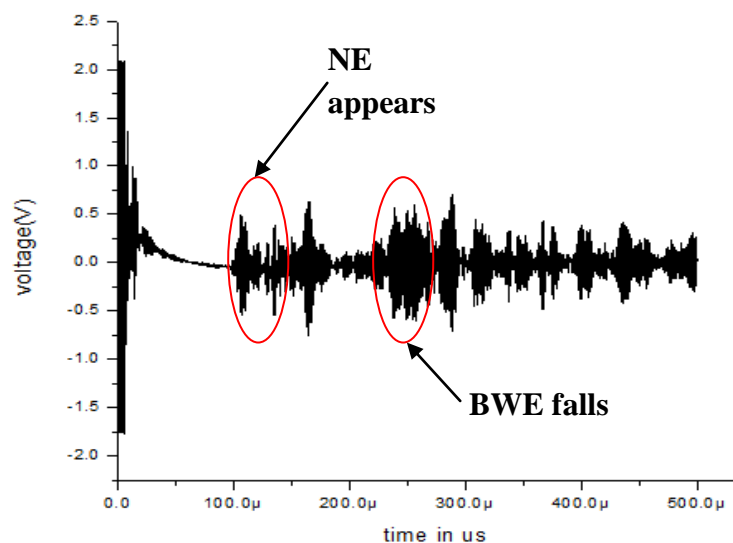
### 4.3.2.1 RESULTS AND DISCUSSIONS

In this plate the notch was symmetrical. The depth of notch was increased by 0.5mm each time after taking readings in PE mode by all the three transducers. The notch was made on horizontal milling machine with HSS milling cutter of 2" diameter and 2mm thickness. Readings were taken on three different locations as shown in **figure 4.2**.

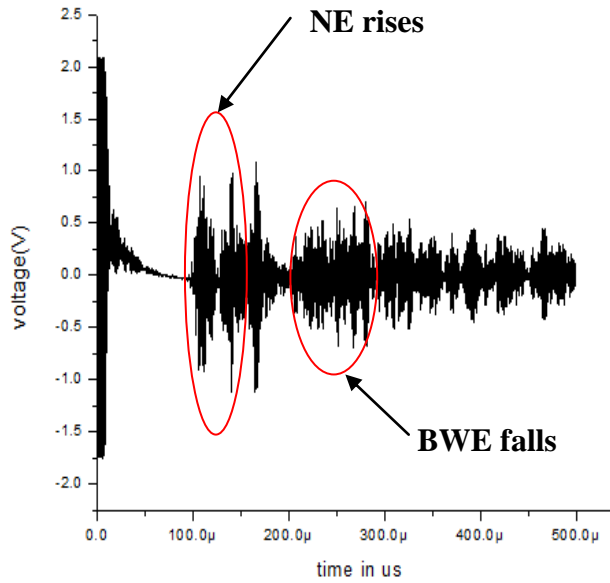
Below are the signatures of all the transducers at three different locations and with different depths of notch made in the plates. **Figure 4.18, 4.19, 4.20** shows the signatures of 0.5MHz, 1MHz and 2MHz at various depths of notch.



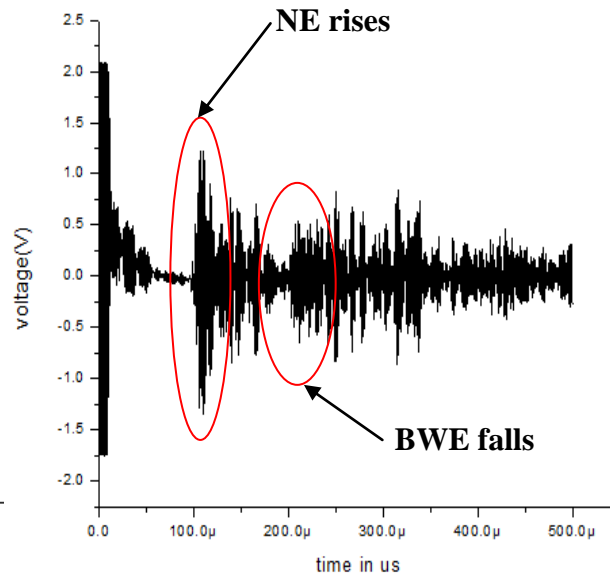
(a) Healthy plate



(b) 25% notch plate



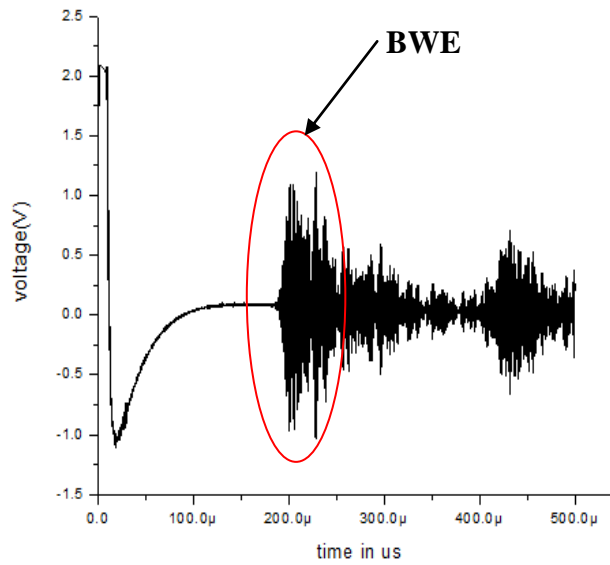
(c) 50% notch plate



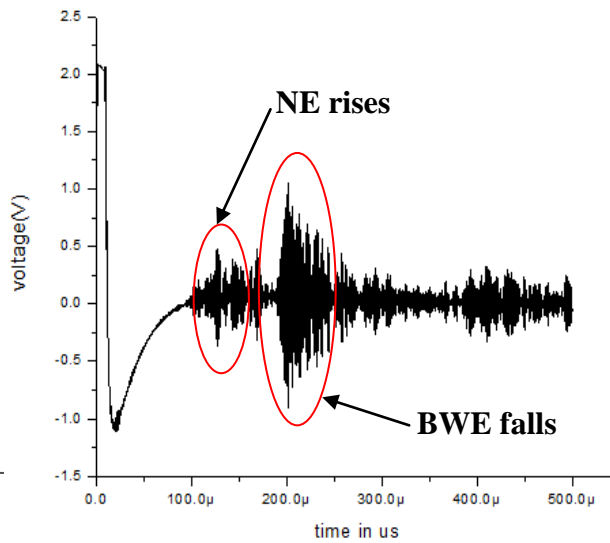
(d) 75% notch plate

Figure 4.18: PE Signatures with 0.5MHz

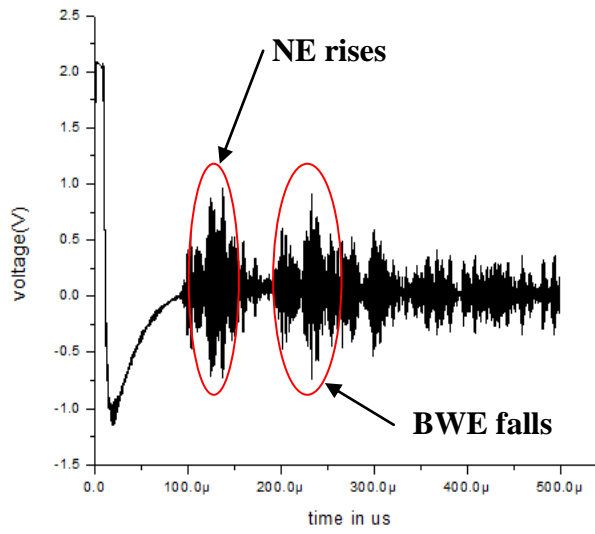
Signatures of 1MHz transducer at various depths of notch are given below.



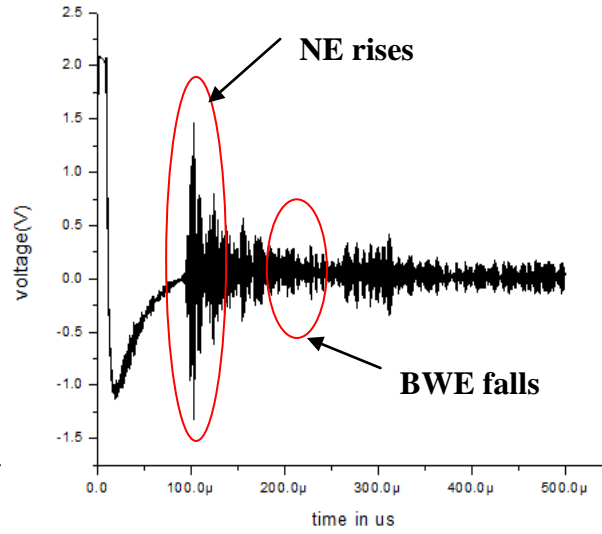
(a) Healthy plate



(b) 25% notch plate



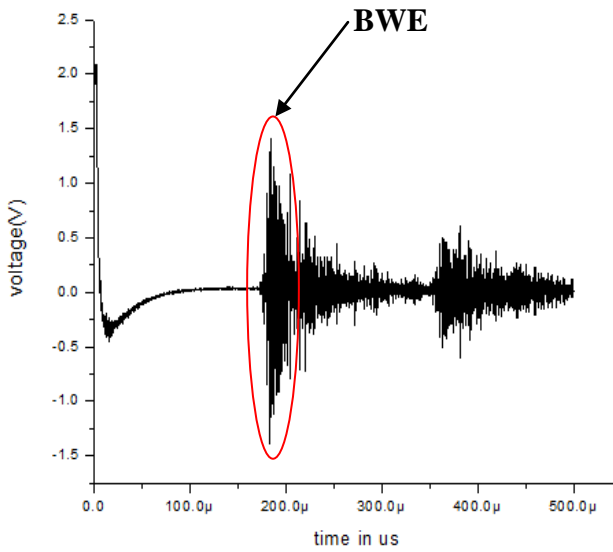
(c) 50% notch plate



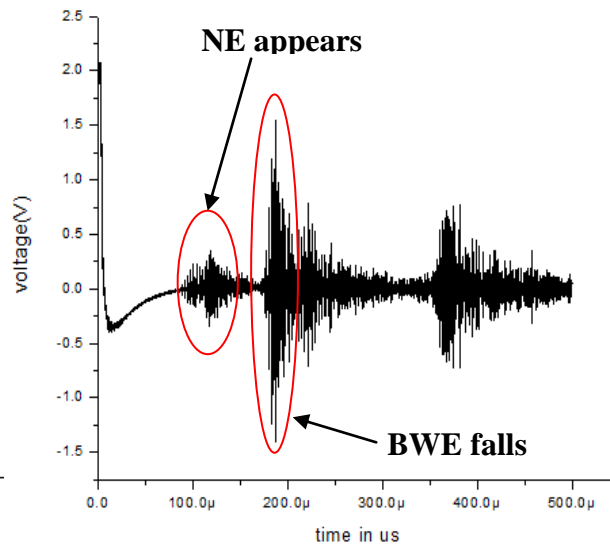
(d) 75% notch plate

Figure 4.19: PE Signatures with 1MHz

Signatures of 2MHz transducer at various depths of notch are given below.



(a) Healthy plate



(b) 25% notch plate

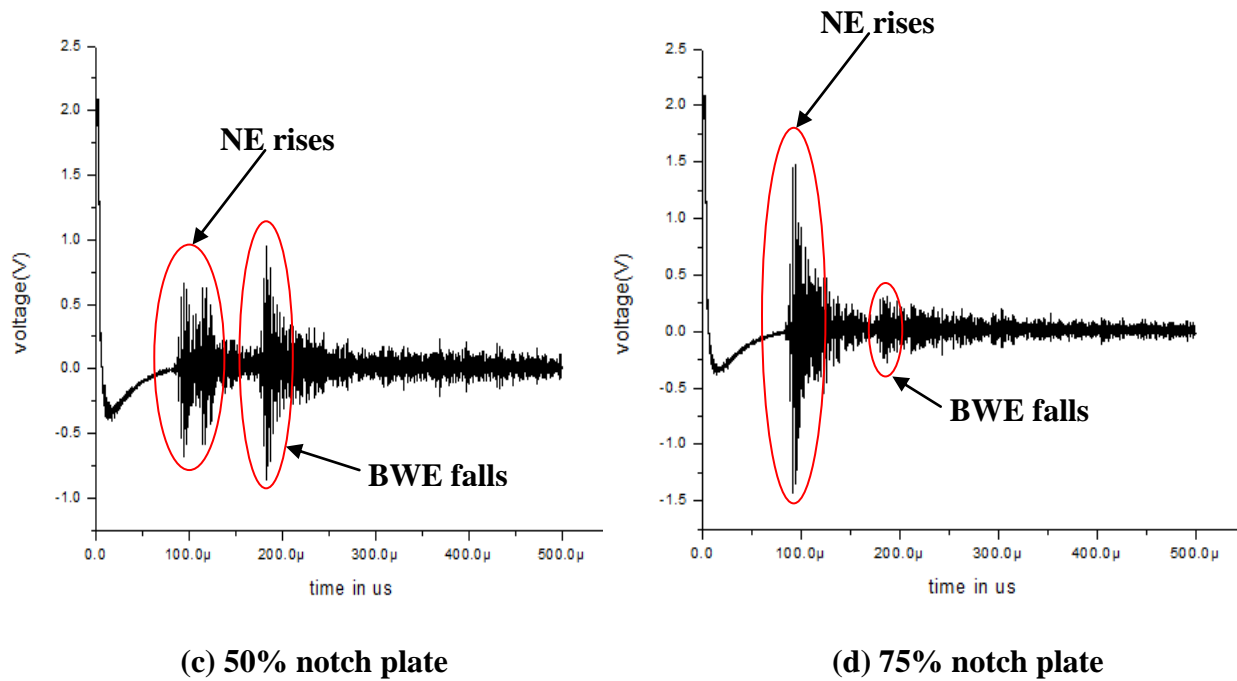


Figure 4.20: PE Signatures with 2MHz

Trends of fall in peak to peak voltage of back wall echo and rise in peak to peak voltage of notch echo for 0.5MHz frequencies used is shown in plots below in **figure 4.21, 4.22**.

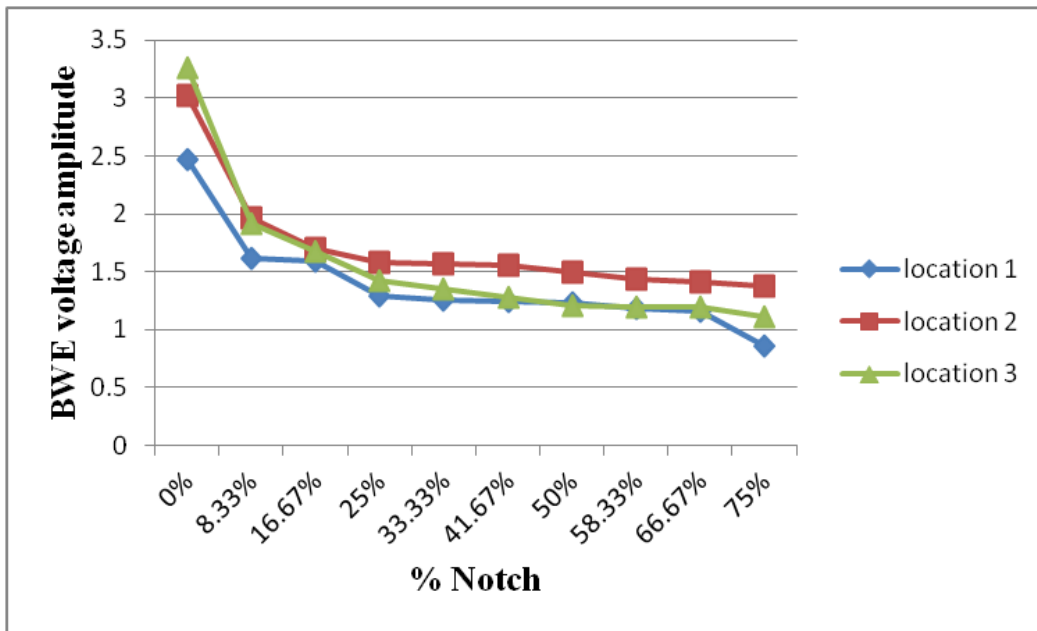
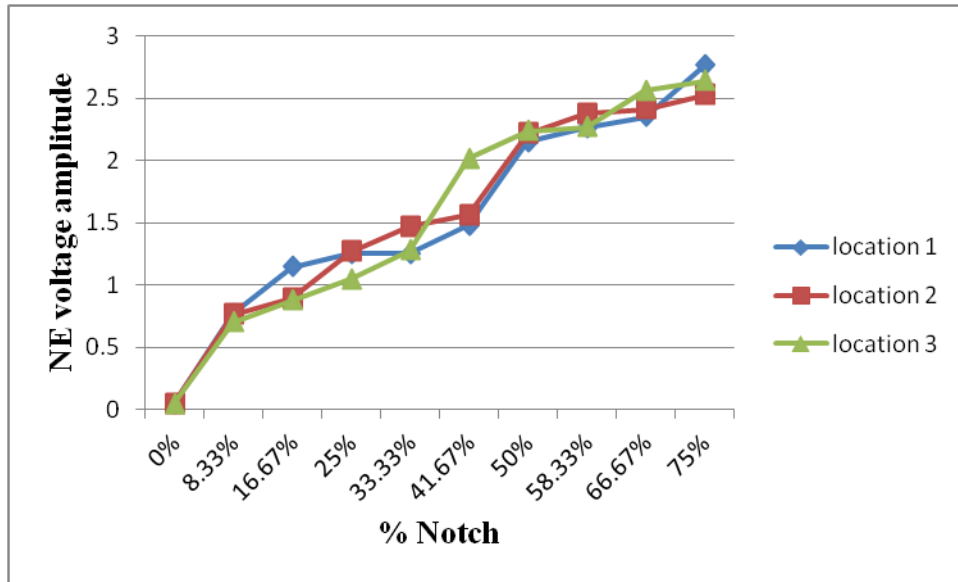
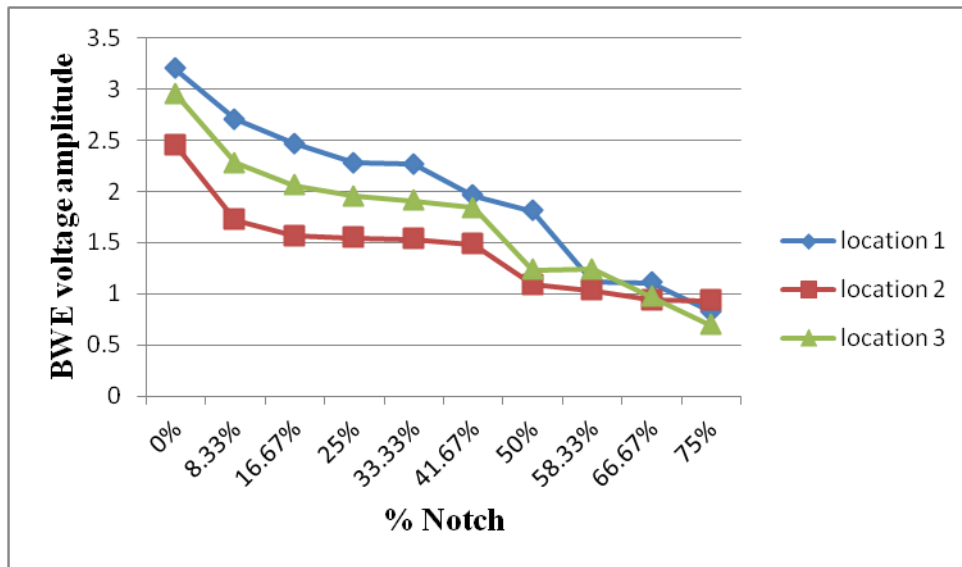


Figure 4.21: Voltage amplitude of BWE (0.5MHz)



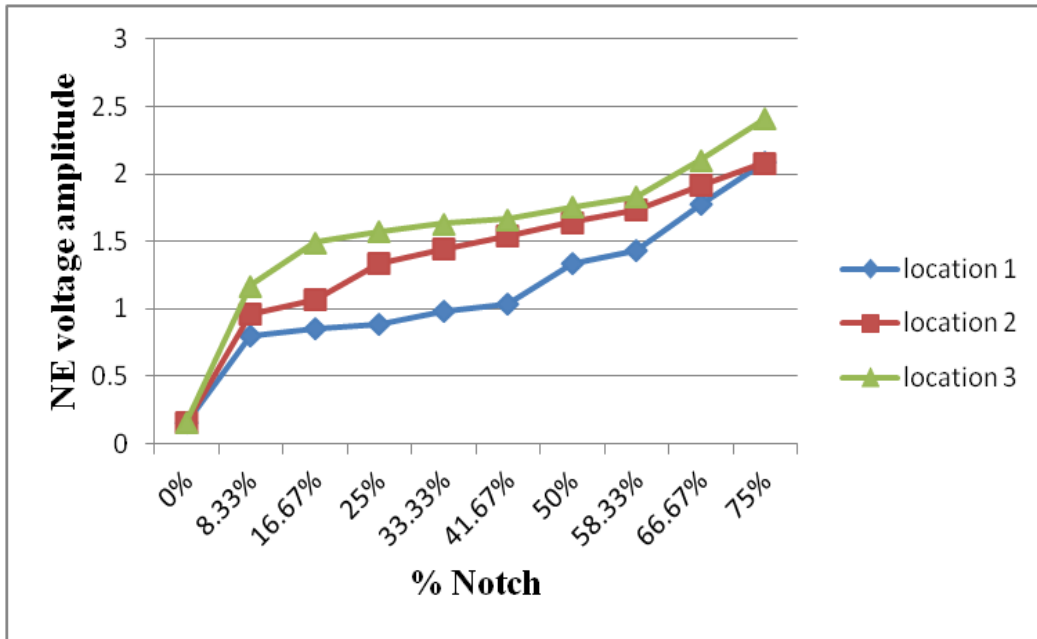
**Figure 4.22: Voltage amplitude of NE (0.5MHz)**

Trends of fall in BWE and rise in NE for 1MHz frequency is shown in **figure 4.23, 4.24**.



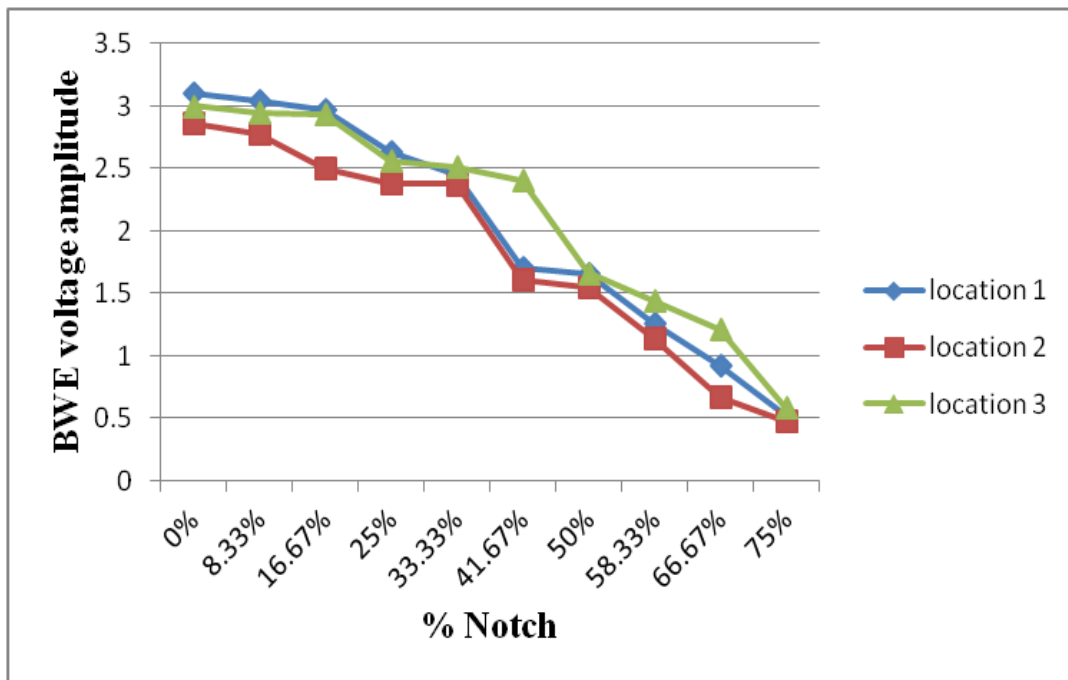
**Figure 4.23: Voltage amplitude of BWE (1MHz)**

1MHz frequency is well suited for notch detection as there is almost regular trend of fall in BWE and rise in NE as in **figure 4.23, 4.24**. Moreover results are almost similar on all the three locations of testing. So this implies that the repeatability which is important for any experiment is possible in this case.

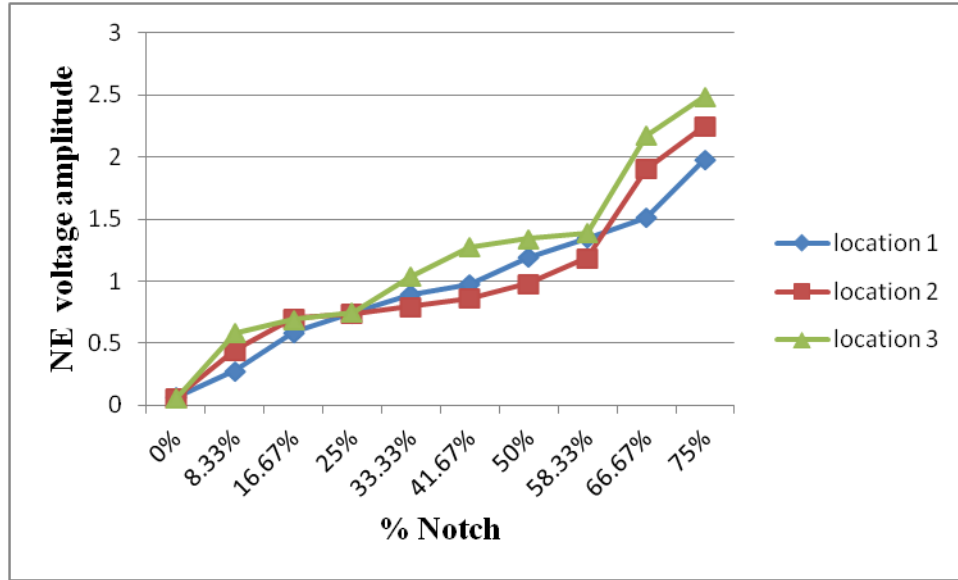


**Figure 4.24: Voltage amplitude of NE (1MHz)**

Trends for fall in BWE and rise in NE for 2MHz is shown in **figure 4.25, 4.26.**



**Figure 4.25: Voltage amplitude of BWE (2MHz)**



**Figure 4.26: Voltage amplitude of NE (2MHz)**

Similar to 1MHZ, 2MHz frequency also responds well for notch detection as there is almost regular trend of fall in BWE and rise in NE as in **figure 4.25, 4.26**. Moreover results are almost similar on all the three locations of testing. So this implies that the repeatability which is important for any experiment is possible in this case.

From the signatures shown and trends for various percentages of notches shown above, following observations were made which are similar to previous study of plate with one sided notch.

- 1) Appearance of Notch Echo (NE) in notched plate as shown in **figure 4.18, 4.19, 4.20** as compared to healthy signatures of that plate as shown in figure indicates the presence of notch can be detected by all the three frequencies used.
- 2) Location of damage can be determined. As we know in PE method  $D = \frac{v \times t}{2}$

Where, “v” is the velocity of particular mode,

“t” is the time of flight,

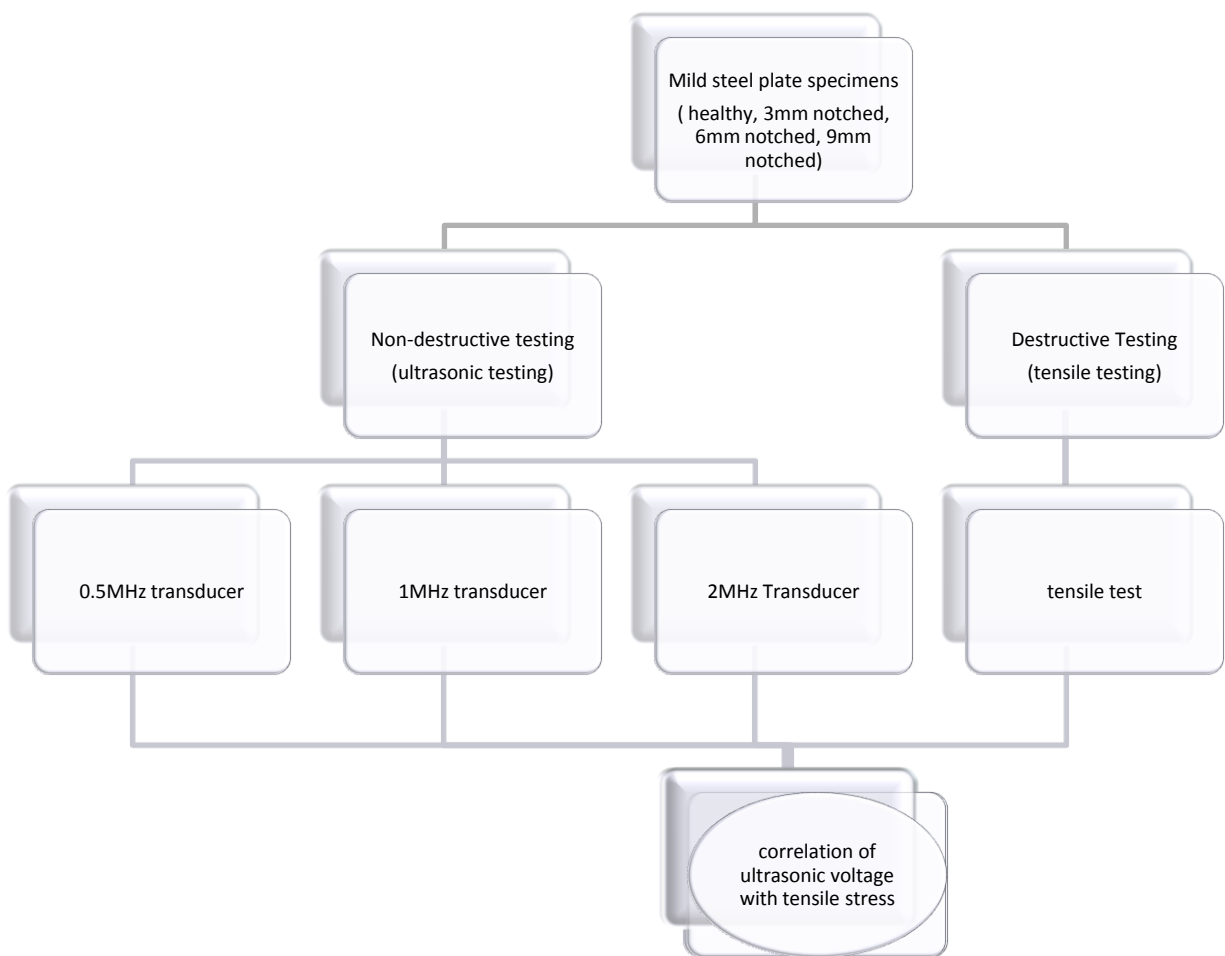
“D” is the length of plate in which wave is travelling.

From above three parameters “v” can be determined from dispersion curve for a particular mode and “t” can be determined from the given signature. So we can very easily estimate distance “D” from where the guided wave is reflected. So the defect can be located using above method of defect detection.

3) Magnitude of damage can also be determined in this technique. There are basically two ways in which magnitude of defect can be estimated. Firstly, as the depth of notch increases the BWE falls. Secondly, as the NE rises as the depth of notch increases. So the results can be further quantified to correlate depth of notch with the percentage rise of voltage in NE or percentage fall of voltage in BWE.

#### 4.4 DESTRUCTIVE TESTING AND RESULTS

In this experiment a correlation between ultrasonic voltage and tensile stress was established. Various steps involved in this study are shown in the block diagram below



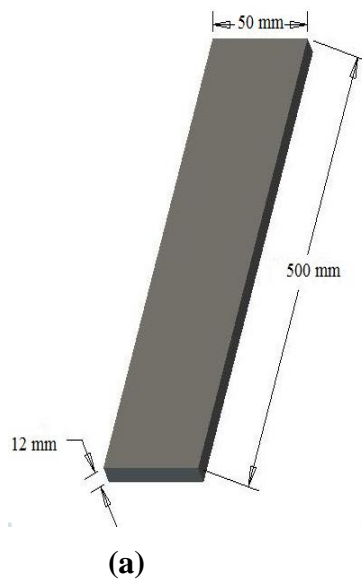
**Figure 4.27: Block diagram representing various steps of study**

#### 4.4.1 Experimental Details for Destructive Testing

**Details of specimen:** - The mild steel plates of the dimension 500mm×50mm×12mm were used in this study as shown in **figure 4.28(a)**. Four specimens of above dimension were taken. Notch of different depths were made in these plates. Reading was taken on single location on all the plates. Details of depth of notch in each plate are given below. Test matrix for destructive testing is shown in **table 4.3**.

**Table 4.3: details of depth of notch in destructive testing**

| Plate no | Depth of notch | Magnitude of defect |
|----------|----------------|---------------------|
| Plate 1  | 0mm            | 0%                  |
| Plate 2  | 3mm            | 25%                 |
| Plate 3  | 6mm            | 50%                 |
| Plate 4  | 9mm            | 75%                 |



**Figure 4.28: (a) dimensions of the healthy specimen, (b) Healthy Specimen**

**Setup:** - A Universal Tensile testing machine shown in Fig. has been used for the testing of mild steel plates for its tensile strength. Maximum Capacity of UTM is 1000 kN. The test specimens have been prepared according to ASTM-D-3790. This is computer controlled machine having hydraulic grippers for holding the specimen. This machine is capable of performing both tensile as well as compression tests. This machine has been used for subjecting the specimens at different levels of mechanical loading.



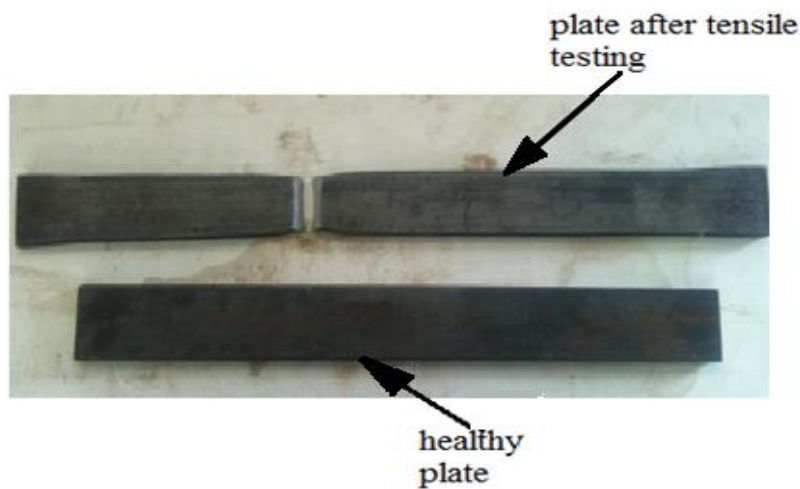
(a)



(b)

**Figure 4.29: (a) Universal Testing machine, (b) setup for tensile testing on UTM**

Location of damage i.e. notch was made at the length  $L/2$ . Four specimens were taken in this study. For first specimen ultrasonic signal was taken and then its tensile testing was done on Universal testing Machine. For second specimen after taking healthy ultrasonic signal, a 3mm notch was made on it. Again its ultrasonic signal was taken and its tensile testing was done on UTM. Similar procedure was followed for specimen 3<sup>rd</sup> and 4<sup>th</sup> having depth of notch as 6mm and 9mm respectively.



**Figure 4.30: Before and after tensile testing of plate**

#### 4.4.2 Results of Tensile Testing

The machine has the maximum capacity of generating 1000kN force. Its speed can be manually set from the control panel. The speed set for all the plates was 100KN/min. results of tensile testing are shown in **table 4.4**.

**Table 4.4: Results of tensile testing of all the specimens**

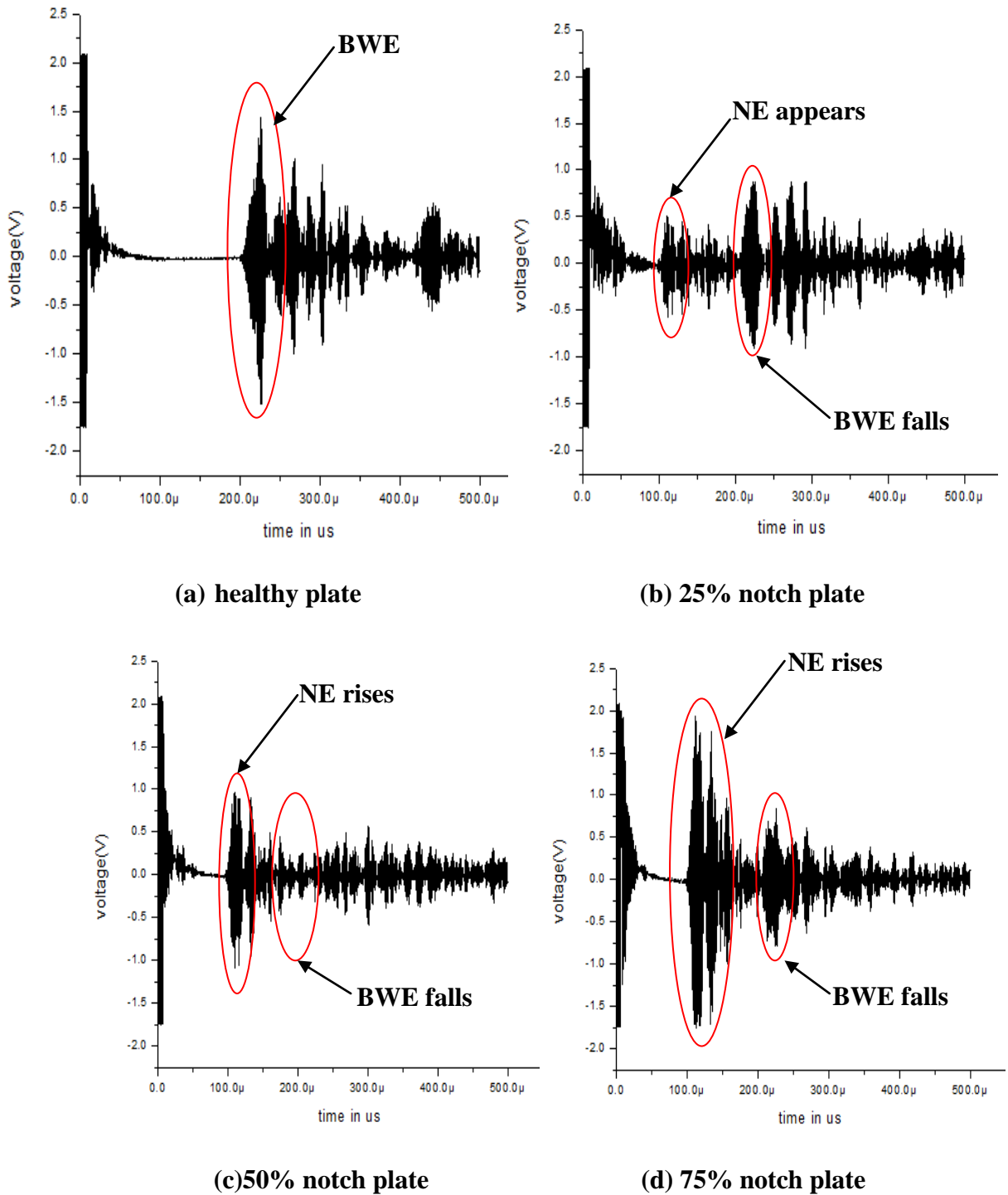
| <b>Specimen</b>        | <b>tensile stress(N/mm<sup>2</sup>)</b> |
|------------------------|---|
| <b>Healthy plate</b>   | <b>528.6235</b>                         |
| <b>25% notch plate</b> | <b>410.84</b>                           |
| <b>50% notch plate</b> | <b>278.8</b>                            |
| <b>75% notch plate</b> | <b>170.125</b>                          |

From the table shown above it is clear that with the increase in depth of notch there is decrease in tensile stress in the plate. Almost linear trend is followed in decrease in tensile stress. So further a study is done to approximately determine the tensile strength of plate using ultrasonic technique by correlating tensile stress obtained by tensile testing with change in ultrasonic voltage amplitude.

#### 4.4.3 Ultrasonic Testing- Results and Discussions

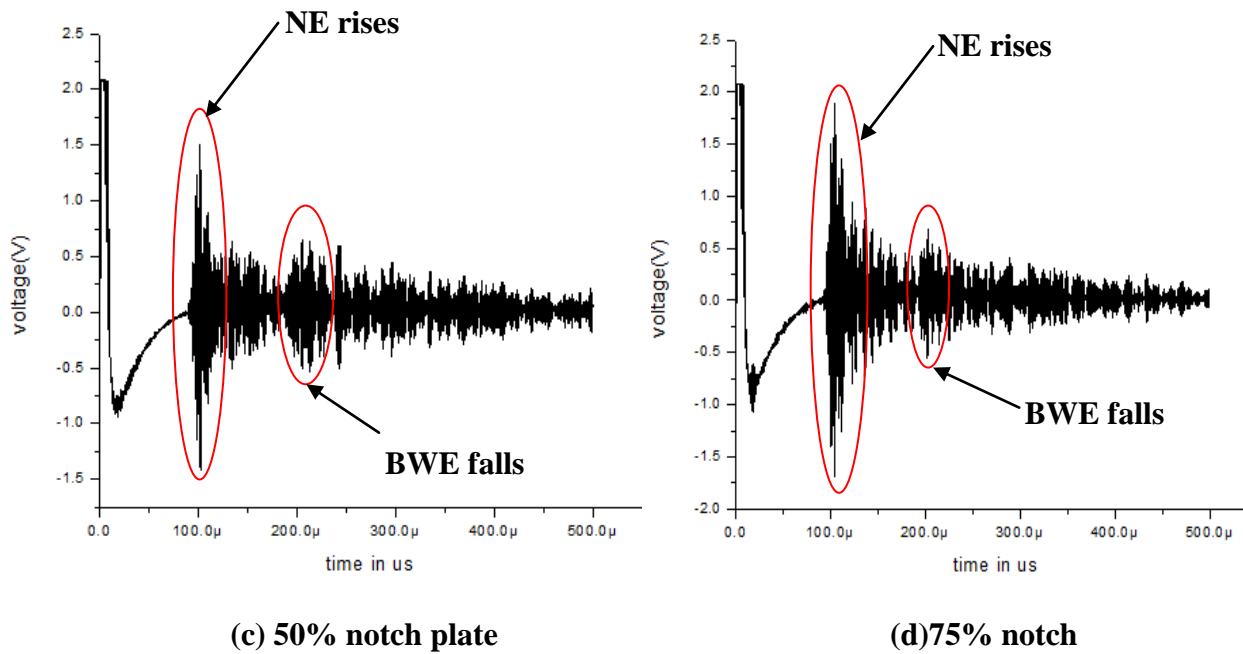
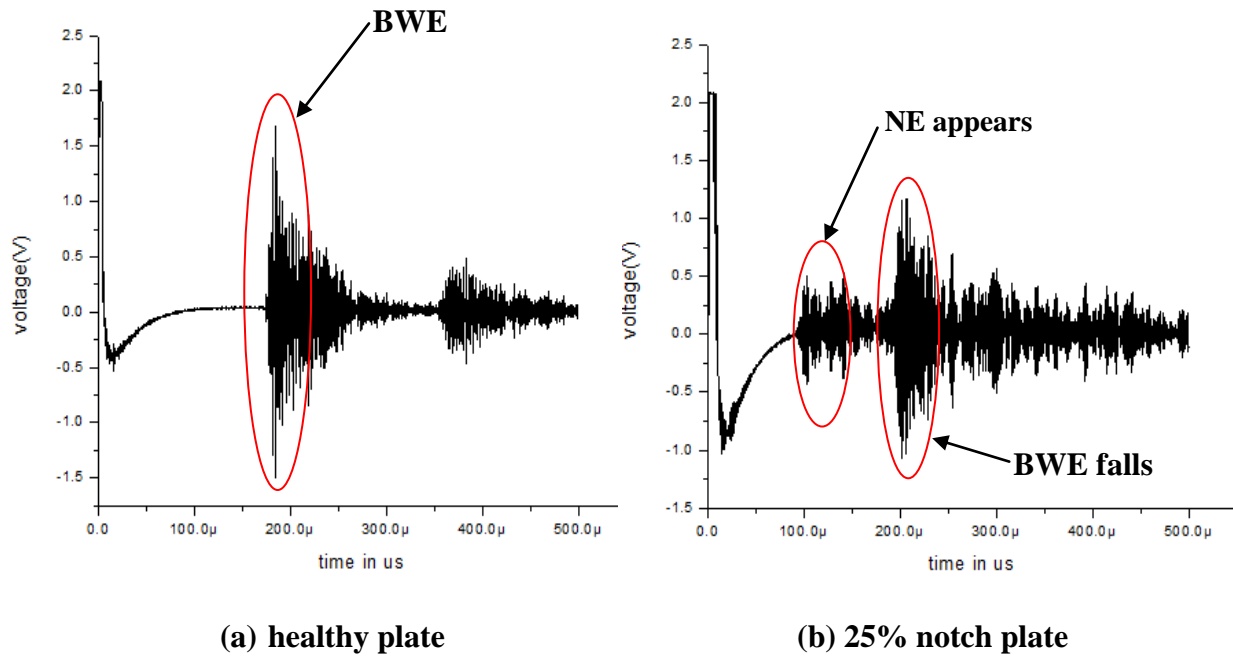
In this study all the specimens first of all tested using guided waves and then tensile testing was done. Readings were taken in PE mode by 0.5MHz, 1MHz and 2MHz transducers on a single location of all the four specimens. For 0.5MHz frequency S1 mode is excited in the plate. For 1MHz frequency S2 mode is excited in the plate. Similarly for 2MHz S5 mode is excited in the plate.

The ultrasonic signatures with 0.5MHz frequency the plates are given below in **figure 4.31**. Fall in BWE and rise in NE is clearly depicted in the signatures with the increase in depth of notch.



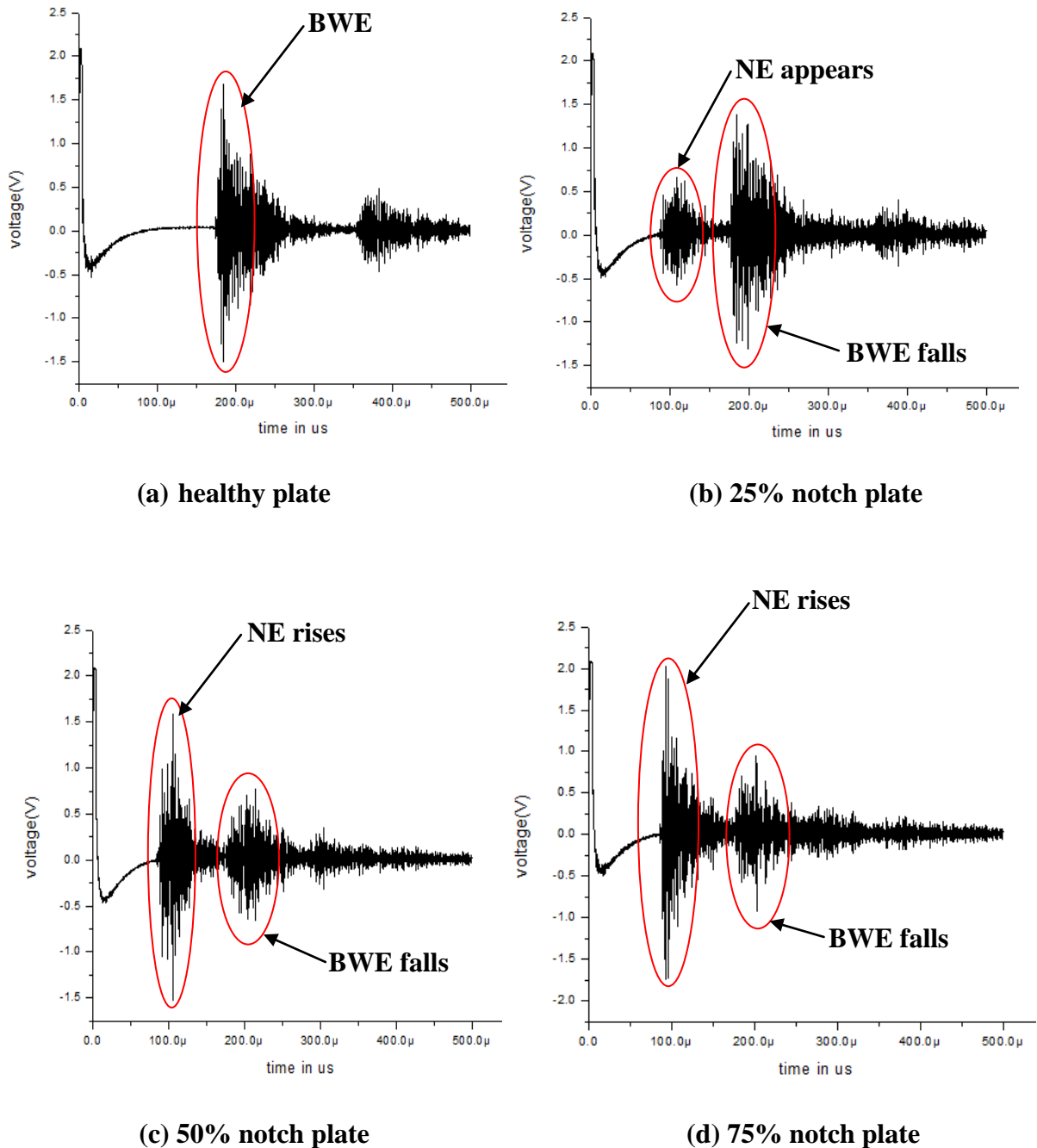
**Figure 4.31: PE signatures with 0.5MHz**

Signatures for 1MHz frequency in PE mode are given in **figure 4.32** at various depths of notch. Behavior of S2 mode of excitation was studied as this mode as it most prominent in this frequency.



**Figure 4.32: PE signatures with 1MHz**

Signatures for 2MHz frequency in PE mode are given in **figure 4.33** at various depths of notch. Behavior of S5 mode of excitation was studied as this mode which was most prominent in this frequency.



**Figure 4.33: PE signatures with 2MHz**

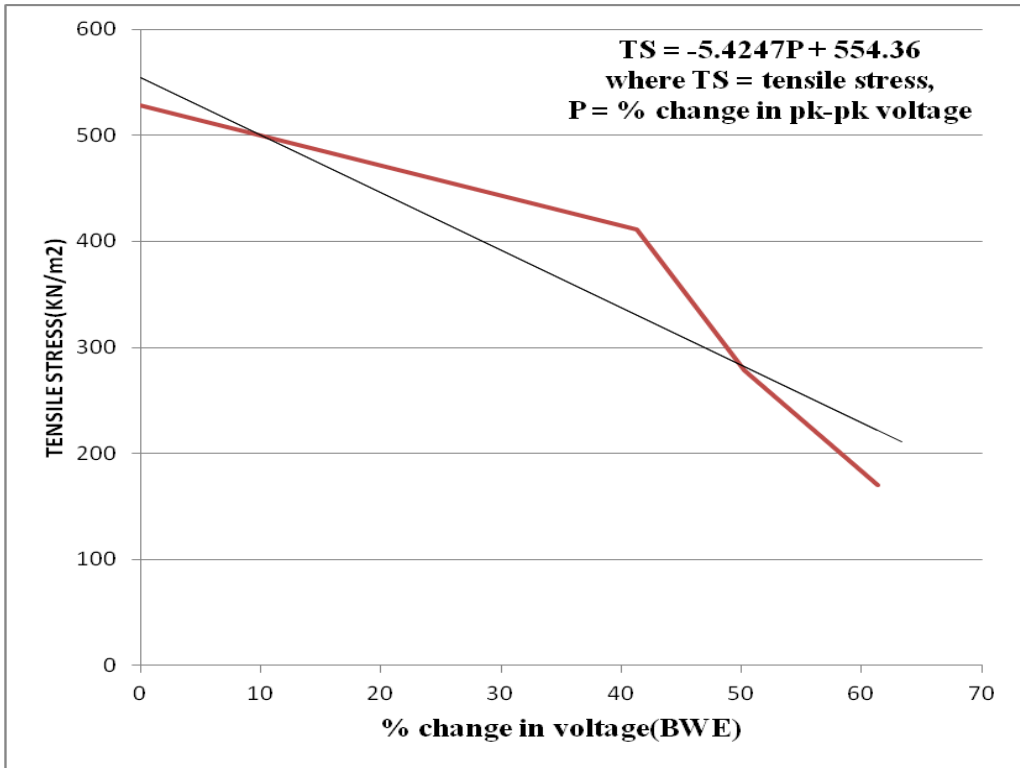


Figure 4.34: Plot of tensile stress vs % change in pk-pk voltage of 0.5MHz frequency

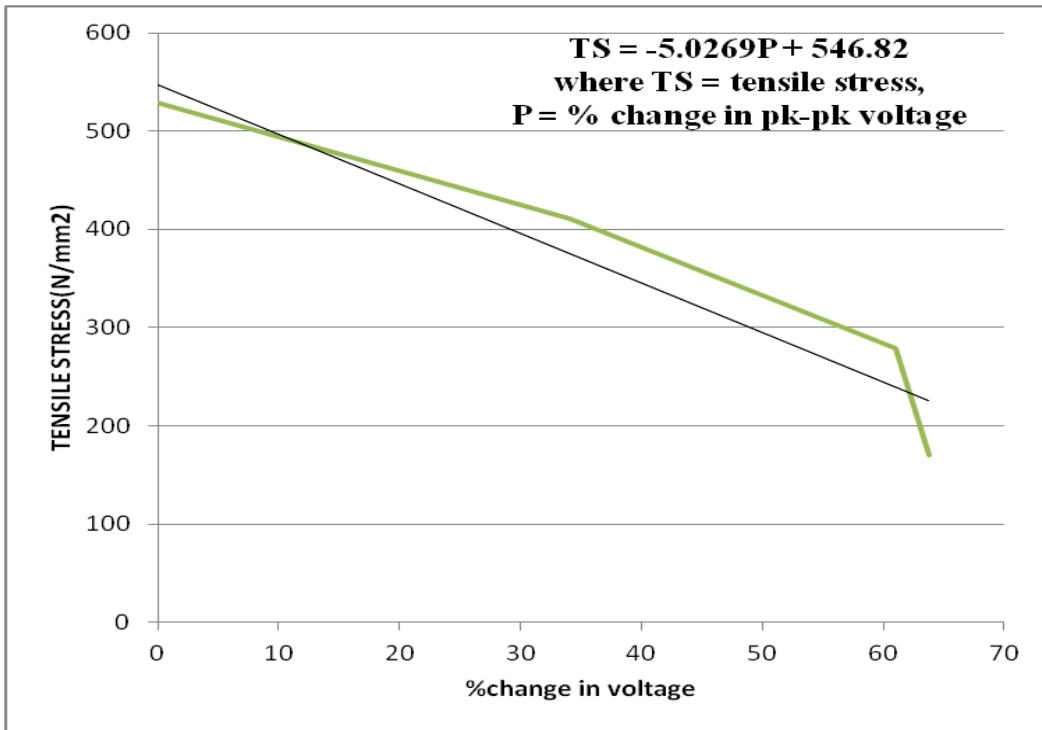
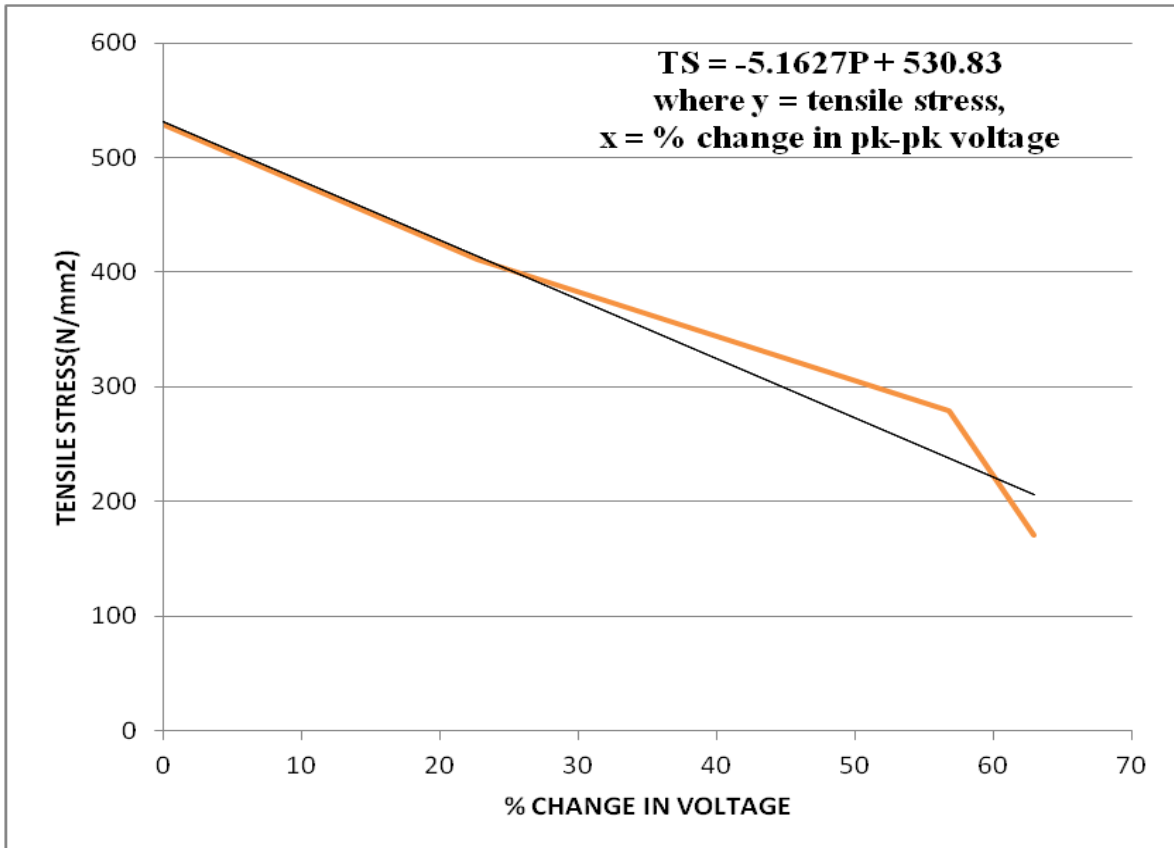


Figure 4.35: Plot of tensile stress vs % change in pk-pk voltage of 1MHz frequency



**Figure 4.36: Plot of tensile stress vs % change in pk-pk voltage plot for 2MHz frequency**

From the results shown **figure 4.34, 4.35, 4.36** almost a linear relationship was established between tensile stress and percentage change in voltage of BWE. Basically three straight line equations were obtained for the three frequencies used. These are as follows,

$$TS = -5.4247P + 554.36 \quad (\text{for } 0.5\text{MHz frequency transducer})$$

$$TS = -5.0269P + 546.82 \quad (\text{for } 1\text{MHz frequency transducer})$$

$$TS = -5.1627P + 530.83 \quad (\text{for } 2\text{MHz frequency transducer})$$

Where, “TS” is tensile stress

And “P” is % change in peak-peak voltage of BWE.

So we can roughly estimate the tensile strength of the plate without actually performing the destructive test by simply taking the ultrasonic signatures. Knowing the % change in

BWE voltage tensile stress can be determined from the above equations of the respective frequency used.

#### **4.5 CLOSURE**

Current chapter discusses the size & specifications of various specimens, experimental setup and methodology for using ultrasonic to monitor damage in the plates using Lamb Waves which subsequently would be made incident on the specimens, with some inherent irregularities. Various machines & equipment used to carry out destructive & non-destructive testing of specimen have been discussed. The reflected /scattered signals would be received. The variations in the signals received lead one to identify, locate and evaluate damage and determine the residual life of the subject plate specimens.

**CORROSION STUDIES**

---

**5.1 General**

In previous chapter simulated notch defect was studied in detailed. Notch is a surface defect which can be a symbolic for other surface defects such as pits, holes and surface cracks. So in this chapter corrosion damage in plates is given which is a surface defect and pitting occurs on surface of plates during corrosion

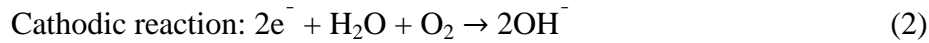
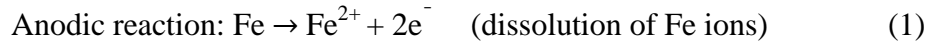
Mild steel plates have wide application in making mechanical structures, equipment and machine components etc. it is known for its good tensile strength, hardness, and many other physical properties. There can be defects that can have adverse affect on its various physical properties. Some are manufacturing defects such as blow holes, welding defects and some defects arise during the time of there service like fatigue, creep and decrease in strength due to corrosion. In this chapter the key area of interest is detection of corrosion in mild steel plates using guided waves.

Corrosion in plates mainly occur due to direct environment attack i.e. exposure to moisture and air, exposure to acidic solution, or its exposure to sea water as in ships etc. There is wide range of corrosion techniques employed for monitoring of corrosion of steel. But existing techniques are electrochemical techniques which relate corrosion rate by its weight loss. Sometimes it's not possible to visually inspect the corrosion like inside the boiler or under surface of ship hull. So implementation of guided waves in such cases can be a better monitoring technique. Sometimes it's not possible to monitor corrosion in situ using other invasive techniques such as x-rays, radiography, acoustic emission. So in such a case guided waves can serve as an important technique for real time corrosion monitoring system.

**5.2 Corrosion mechanism of steel [31]**

Generally steel plates are passivated by an iron oxide film ( $\text{Fe}_2\text{O}_3$ ) that protects the steel. However, the intrusion of chloride ions depassivates steel and is the most important factor in the corrosion of steel. Possible sources of chlorides include aggregates, mix water, admixture (accelerators), deicing chemicals, seawater etc. the chloride content is significantly high in sea

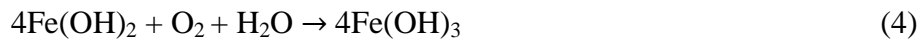
water. Potable water can contain small amount of chlorides ( 20-100 ppm). In the presence of oxygen, water, aggressive ions such as chlorides, steel bars are depassivated and corrosion is initiated. Corrosion is basically an electrochemical process where the anode and cathode are on the same steel bar. At the anode, iron atoms lose electrons to become iron ions ( $Fe^{++}$ ). At the cathode oxygen in the presence of water accepts electrons to form hydroxyl ion ( $OH^-$ ) as shown in **figure 5.1**.



Both the anodic and cathodic reactions are necessary for the corrosion to occur and they need to take place simultaneously. The hydroxyl ions combine with the ferrous ions to form ferrous hydroxide from equation (1) and (2):



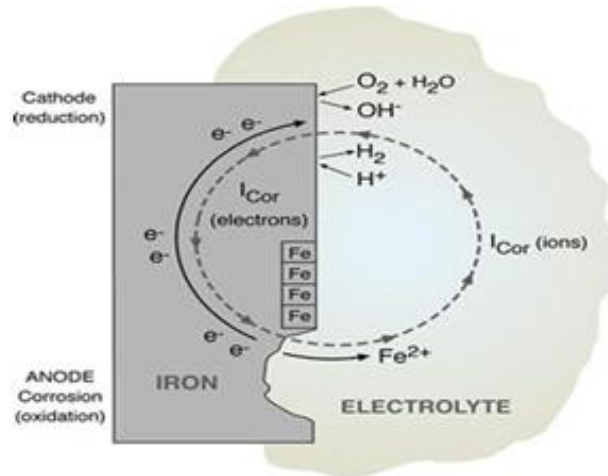
In the presence of water and oxygen, the ferrous hydroxide is further oxidized to form  $Fe_2O_3$ .



(Ferric hydroxide)



(Hydrated ferric oxide- reddish brown rust)

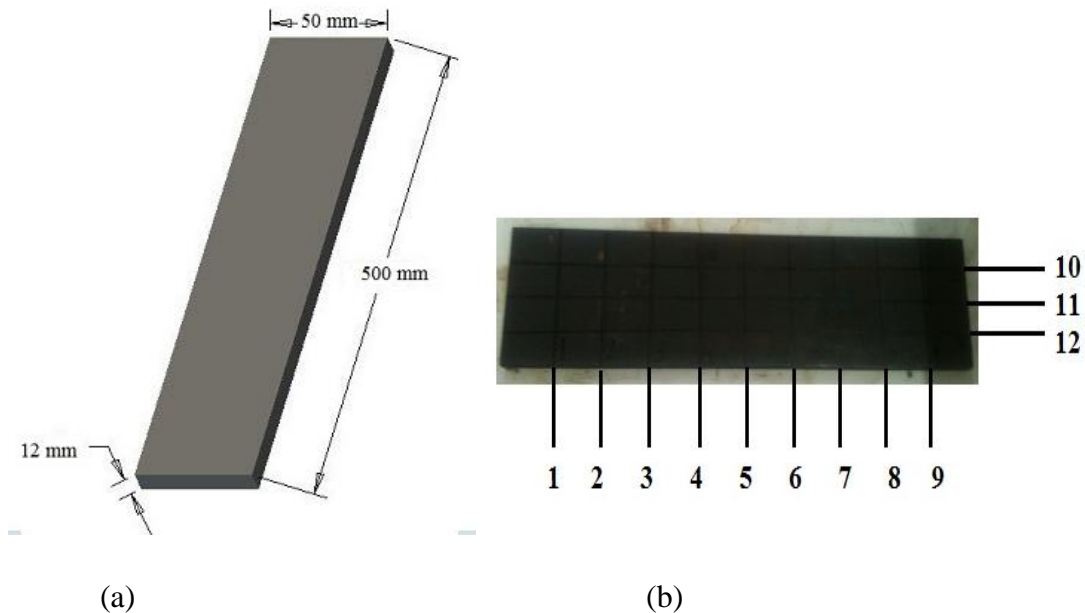


**Figure 5.1: Corrosion Mechanism**

### 5.3 Specimen Details

The mild steel plates of dimension 500mm×114mm×12mm (as in **figure 5.2(a)**) were used. Before starting the electrolysis process the weight of plate was 5351.5gm. The impressed current

corrosion was done using above setup for 24 hours. It was found approximately 8gms of weight was lost during 24 hrs of electrolysis. The equipment used for ultrasonic testing is described in chapter 4.2.2. Then ultrasonic testing in air was done using 0.5MHz, 1MHz, 2MHz in pulse echo mode. Above process was repeated for total 480 hrs (20 days) of impressed corrosion. Readings were taken on total 12 different locations on the plate (**figure 5.2(b)**).



**Figure 5.2: (a) shows dimensions of specimen, (b) shows testing locations on specimen**

#### **5.4 EXPERIMENTAL SETUP FOR ACCELERATED CORROSION**

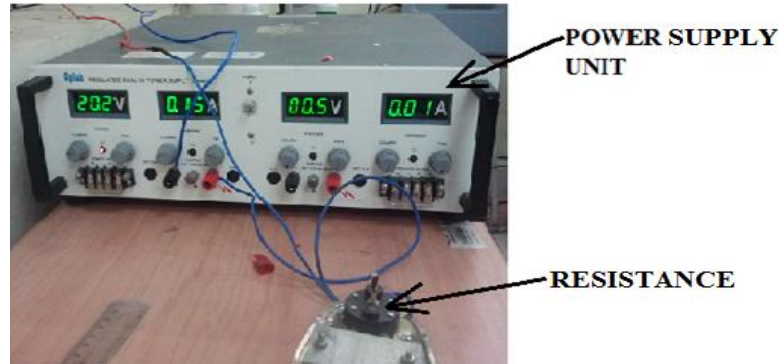
There are many methods to obtain actual corrosion. Few of these methods are listed below:

- 1) By dipping the plates in conc. Nitric acid for few days would result in surface corrosion of plate.
- 2) By impressed current (electrolysis) corrosion.
- 3) By heating the plate in presence of air.
- 4) By placing the plate in water.

From the methods listed above impressed current (electrolysis) method was used to corrode the mild steel specimen. The reason of adopting above is that it is possible to monitor all the stages of corrosion by using this method. Moreover speed of corrosion process can be controlled by simply changing current and voltage settings from the power supply unit.

### 5.4.1 Equipment Used

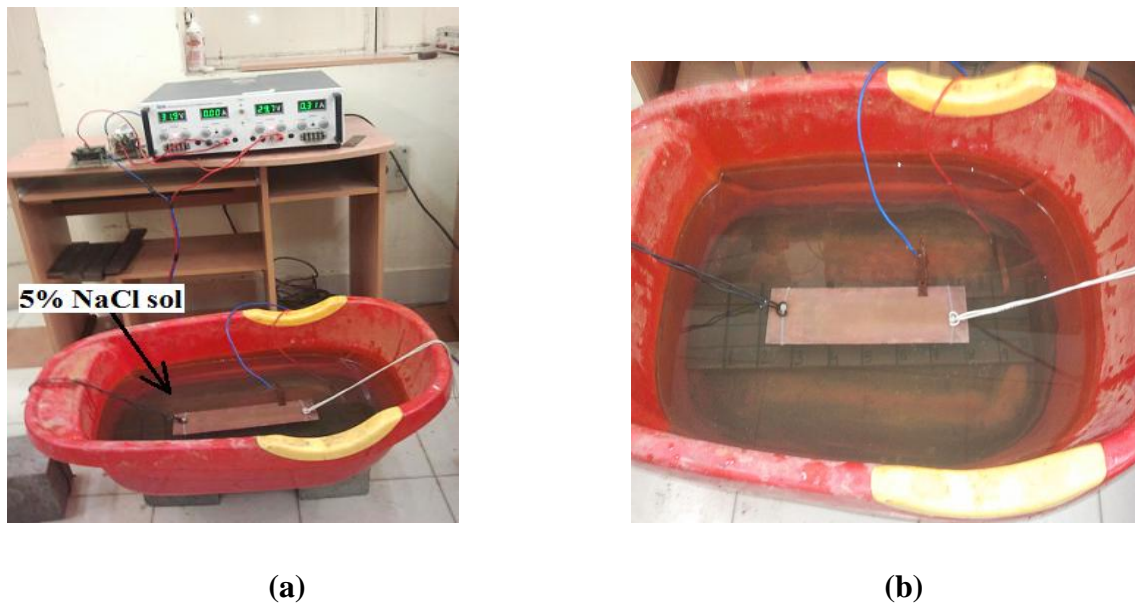
Dual supply 32V power supply unit of Aplab was used. This is constant voltage supply unit. Both current and voltage can be controlled by a knob. Variable resistance of minimum resistance  $80\Omega$  was used. Copper plate was made as cathode and mild steel specimen as anode. Connections are made using copper wires (**figure 5.3**).



**Figure 5.3: Power Supply Unit**

### 5.4.2 Electrolysis setup

Mild steel plate was placed in a plastic tank filled with 20 liters of 5% NaCl solution in water (**figure 5.4**). NaCl solution acts as electrolyte. Copper plate was placed in the tank such that both these plates do not come in direct contact with each other.



**Figure 5.4: (a) setup for impressed current corrosion, (b) mild steel and copper plate arrangement in NaCl sol.**

Both these plates were connected to power supply unit using copper wires. Resistance of  $110\Omega$  was used. When the voltage was set at 30V, current was 0.27A.

## 5.5 RESULTS AND DISCUSSIONS

Corrosion makes the surface of the plate rough which can be easily differentiated by the comparison between fig (a) and (b). Also there is significant weight loss due to corrosion. Ultrasonic signals were taken by 0.5MHz, 1MHz and 2MHz transducers. From the signatures of these frequencies it was detected that BWE falls in case 1MHz and 2MHz as the corrosion increases.



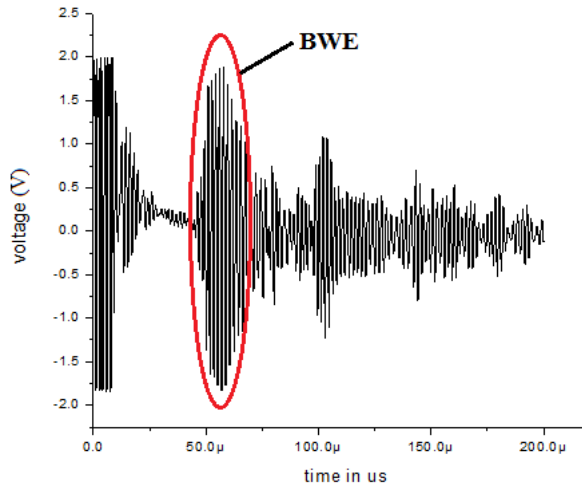
(a)



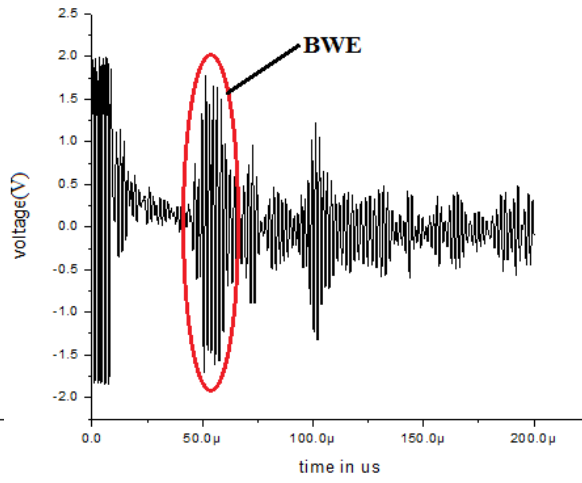
(b)

**Figure 5.5: (a) healthy specimen, (b) after corrosion**

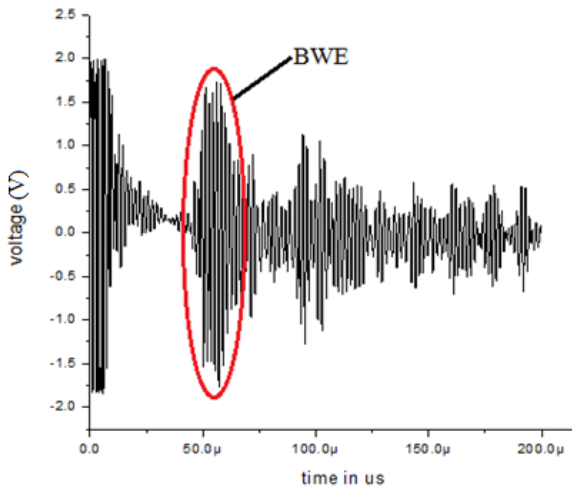
Below are shown the signatures at taken at different locations and the change in BWE as the hrs of corrosion increases.



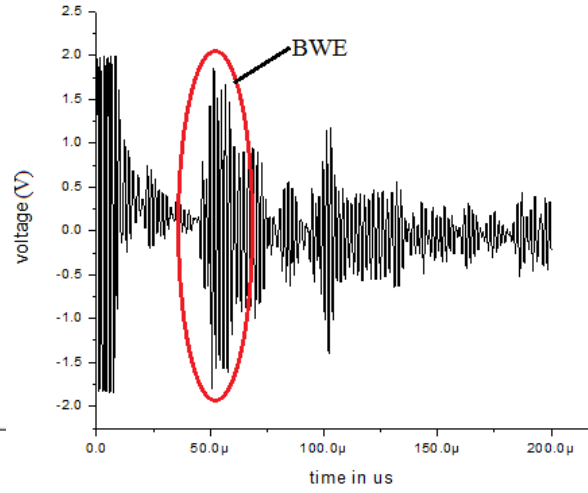
(a) Healthy signature



(b) 144 hrs of corrosion

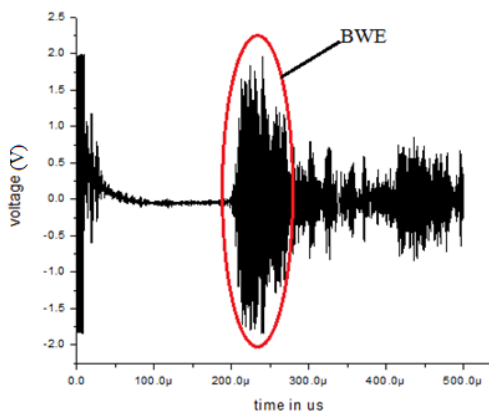


(c) 336 hrs of corrosion

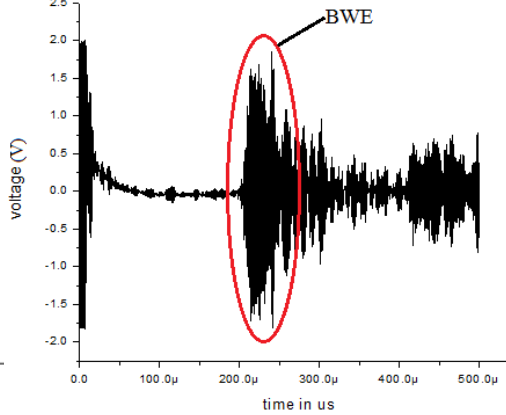


(d) 480 hrs of corrosion

Figure 5.6: Signatures of 0.5MHz frequency at location 4

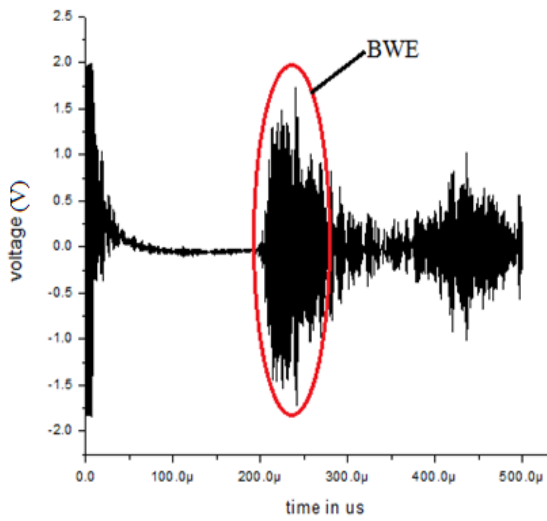


(a) Healthy signatures

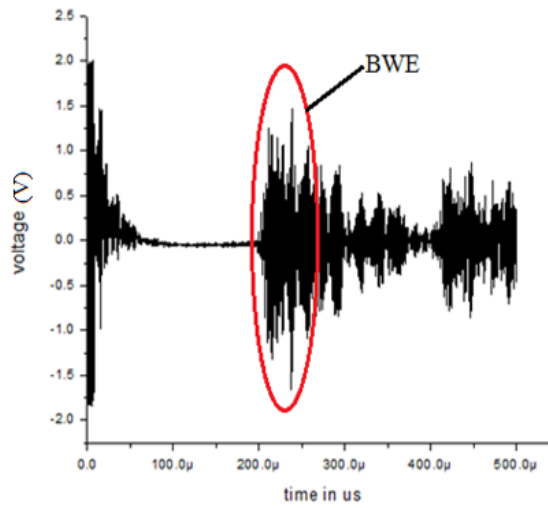


(b) 144 hrs of corrosion

(a)



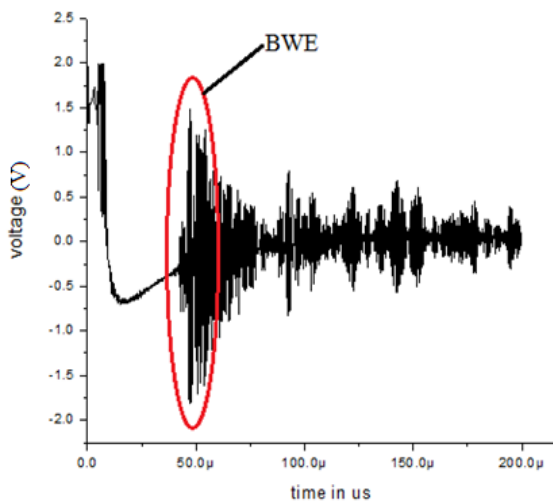
(c) 336 hrs of corrosion



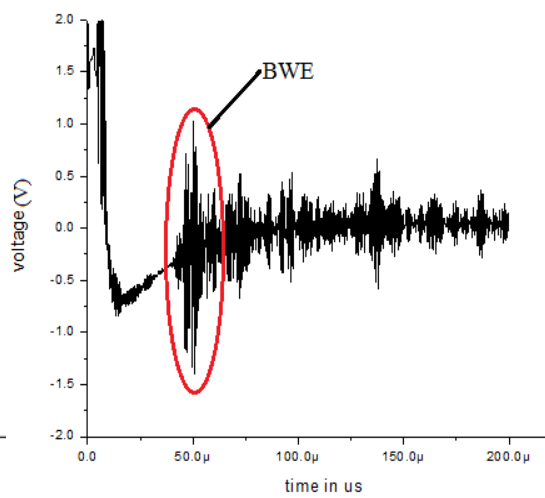
(d) 480 hrs of corrosion

**Figure 5.7: Signatures of 0.5MHz frequency at location 11**

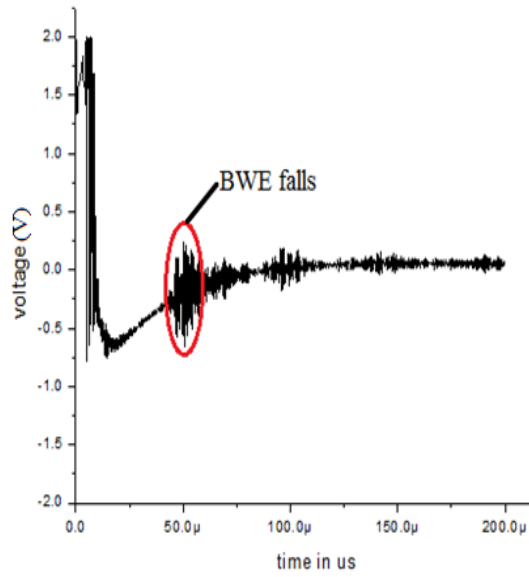
Similarly signatures by 1MHz frequency were taken on all the 12 locations which are shown below in **figure 5.8, 5.9.**



(a) Healthy signatures

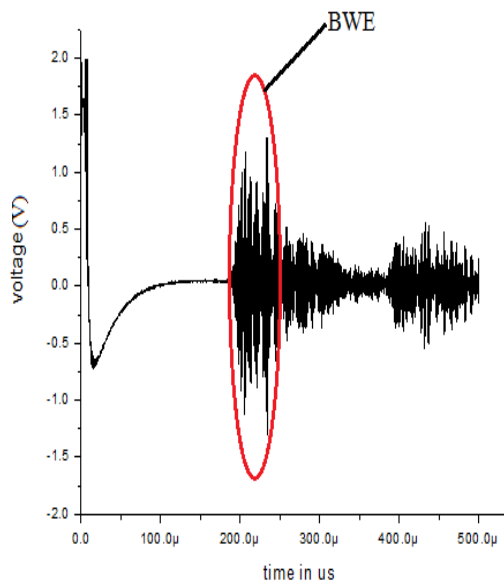


(b) 196 hrs of corrosion

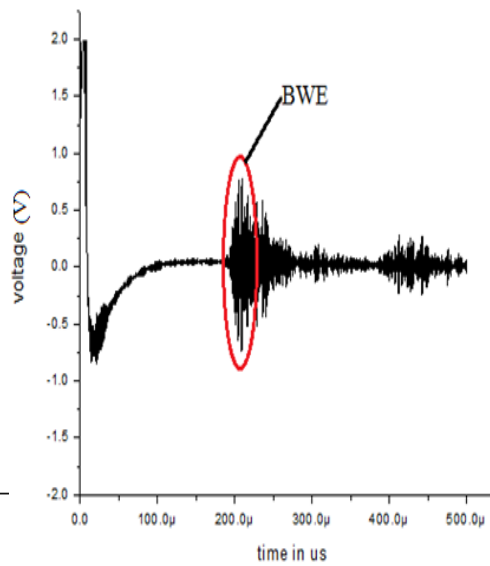


(b) 480 hrs of corrosion

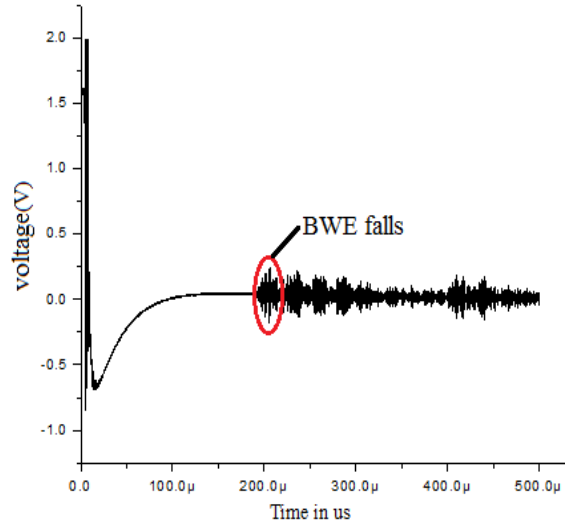
Figure 5.8: Signatures of 1MHz frequency at location 4



(a) Healthy signatures



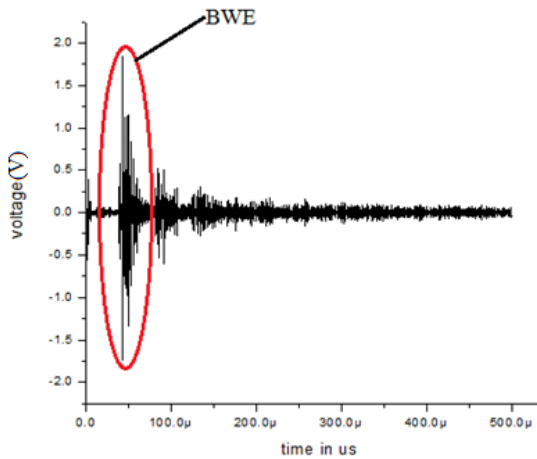
(b) 196 hrs of corrosion



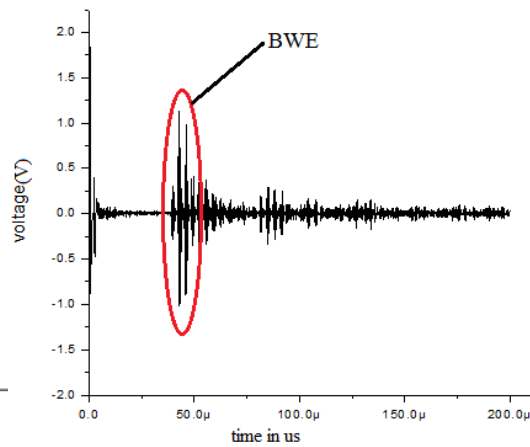
(c) 480 hrs of corrosion

Figure 5.9: Signatures of 1MHz frequency at location 11

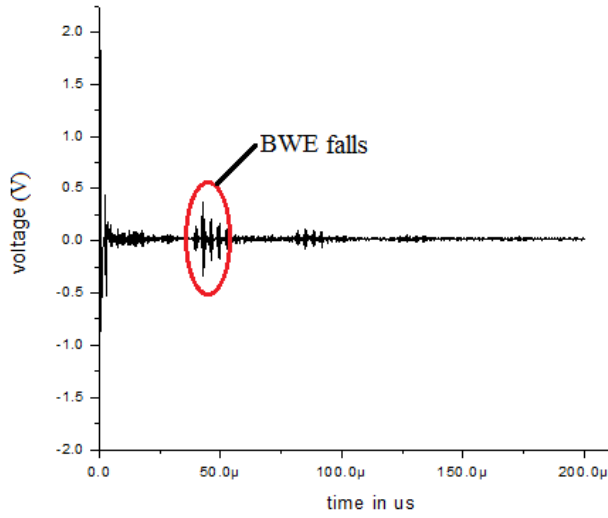
Similarly signatures by 2MHz frequency were taken on all the 12 locations which are shown below in **figure 5.10, 5.11.**



(a) Healthy signatures

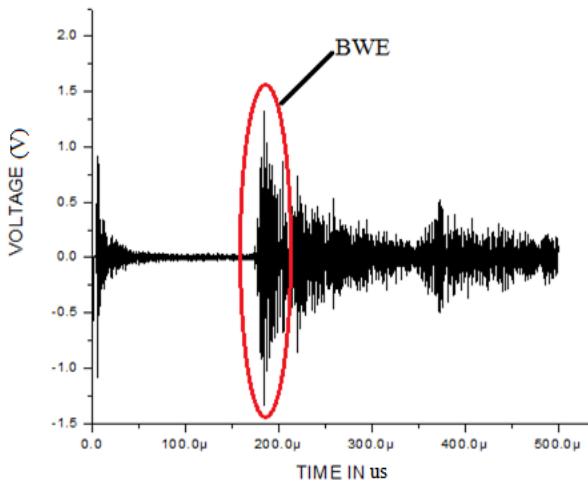


(b) 196 hrs of corrosion

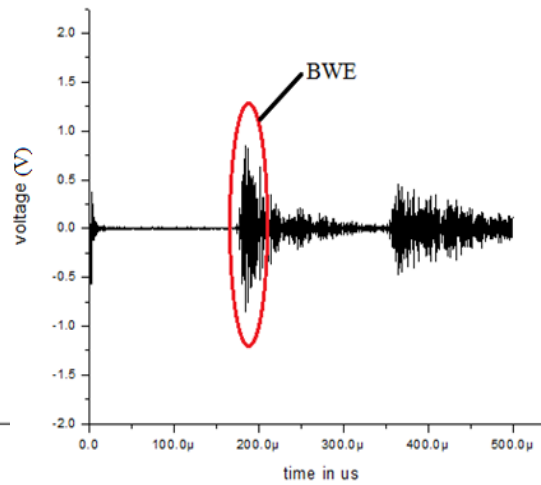


(c) 480 hrs of corrosion

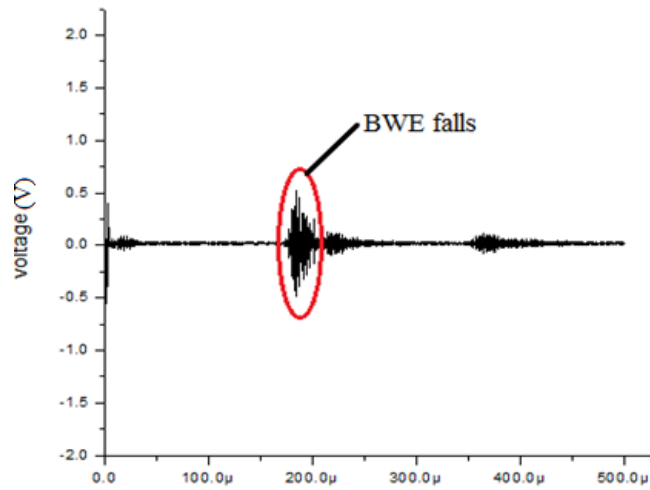
Figure 5.10: Signatures of 2MHz frequency at location 4



(a) Healthy signatures



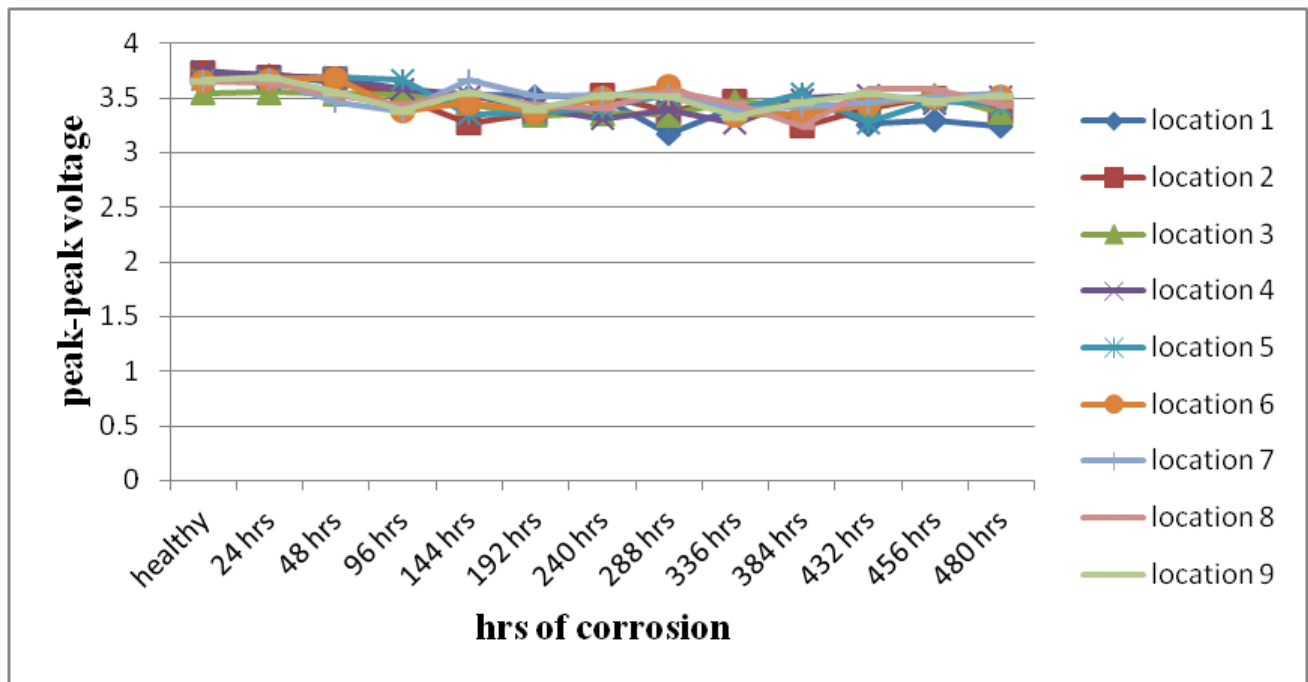
(b) 196 hrs of corrosion



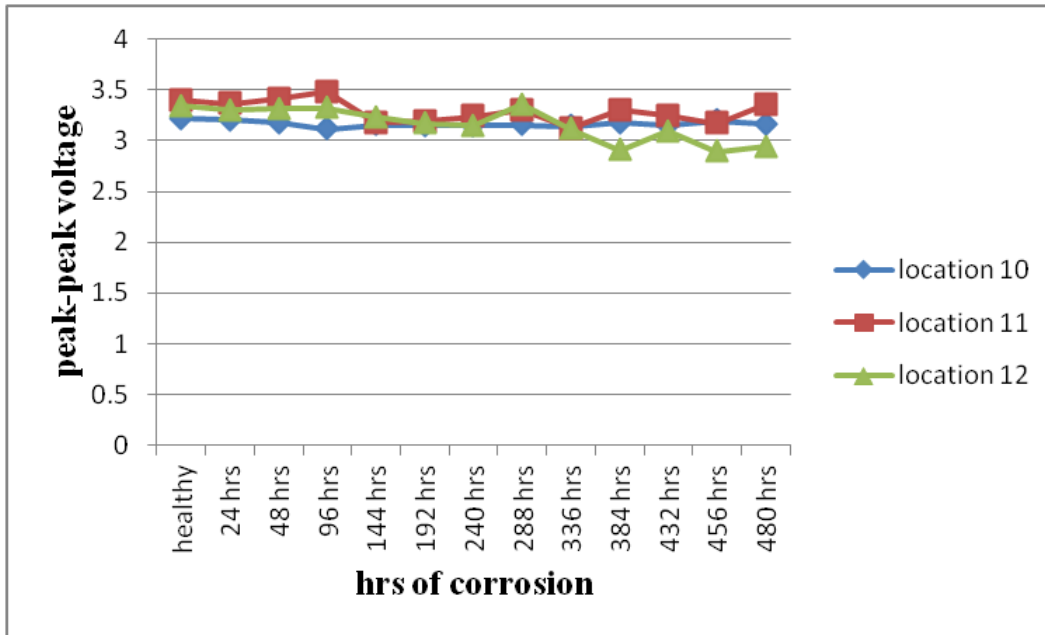
(c) 480 hrs of corrosion

Figure 5.11: Signatures of 2MHz frequency at location 11

Below are given the trends of peak-peak voltage at all the testing locations with 0.5MHz frequency in **figure 5.12(a), (b)**.



(a) Trends of pk-pk voltage for location 1-9

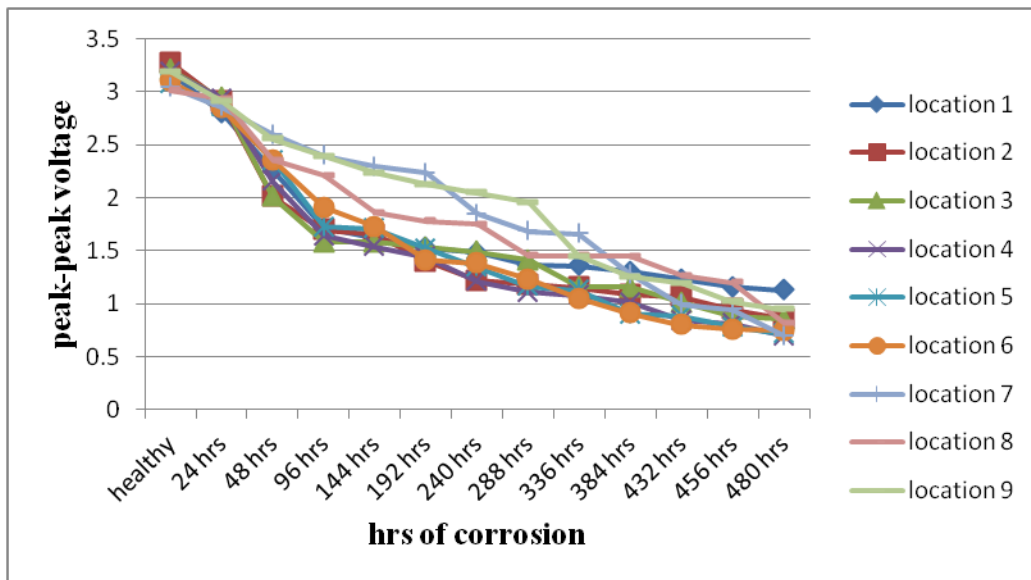


(b) Trends of pk-pk voltage for location 10-12

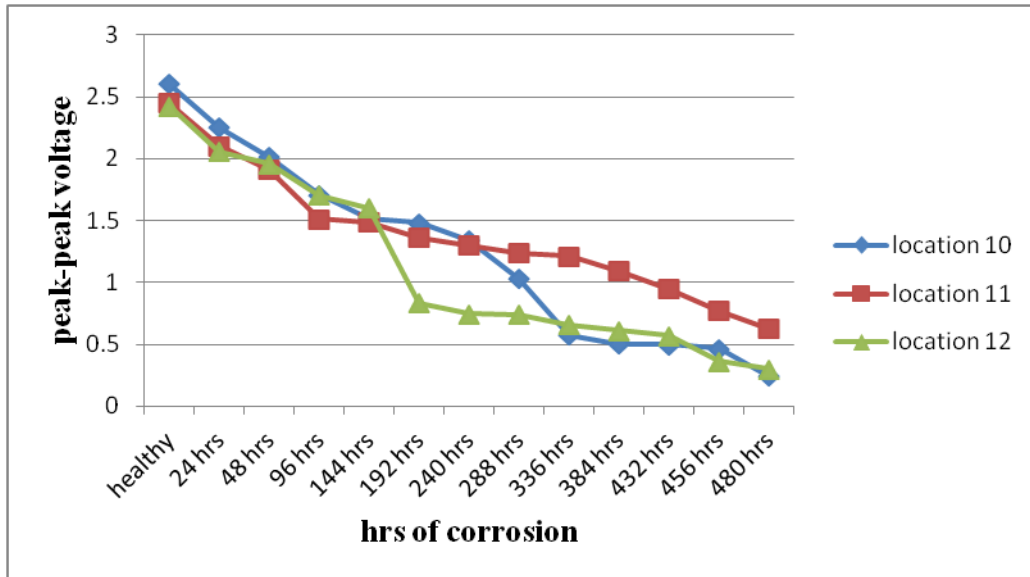
Figure 5.12: Results of 0.5MHz frequency

From the trends of peak-peak voltage it was observed that there was no significant change in the voltage while testing with 0.5MHz.

Below are given the trends of peak-peak voltage at all the testing locations with 1MHz frequency in figure 5.13(a), (b).



(a) Trends of pk-pk voltage for location 1-9

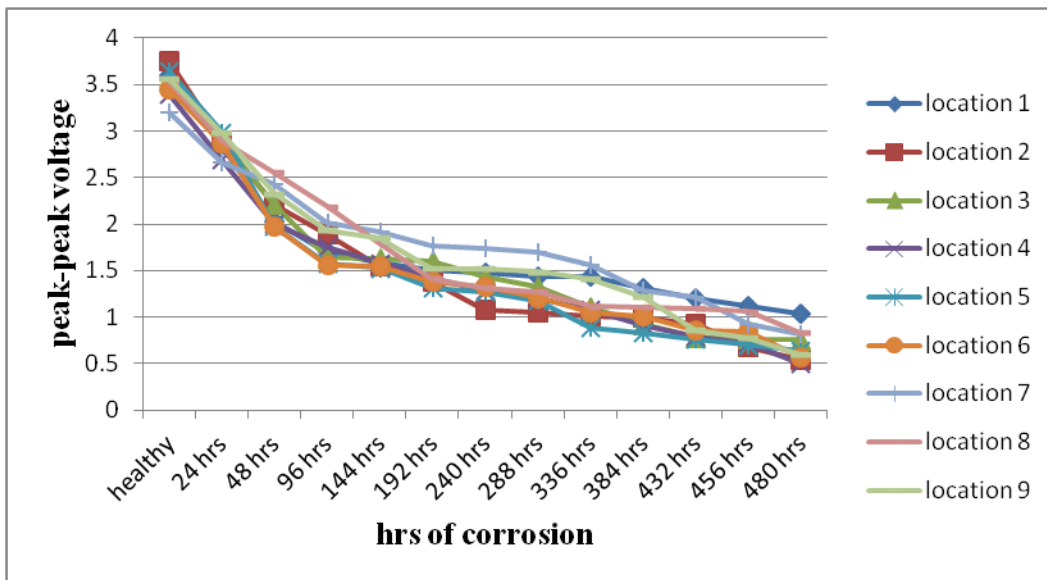


(b) Trends of pk-pk voltage for location 10-12

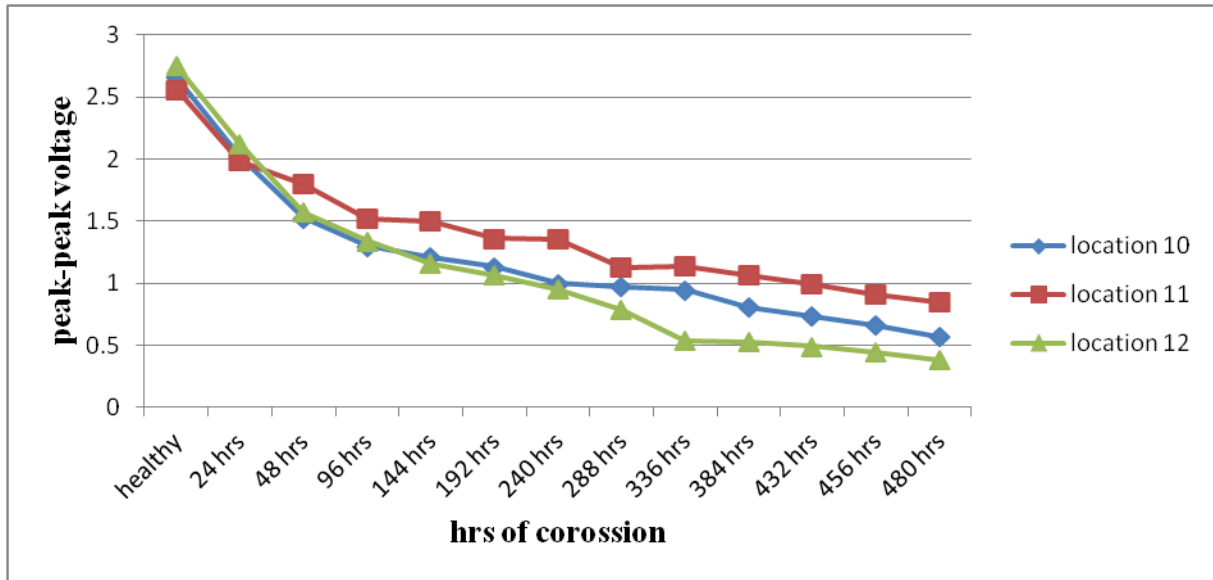
**Figure 5.13: Results of 1MHz frequency**

From the trends of peak-peak voltage it was observed that there was significant drop in the voltage while testing with 1MHz. So corrosion can be easily detected with this frequency.

Below are given the trends of peak-peak voltage at all the testing locations with 2MHz frequency in figure 5.14(a), (b)



(a) Trends of pk-pk voltage for location 1-9



(b) Trends of pk-pk voltage for location 10-12

**Figure 5.14: Results of 2MHz frequency**

From the trends of peak-peak voltage it was observed that there was significant drop in the voltage while testing with 0.2MHz. This frequency can be used for corrosion detection in plates.

### 5.6 CLOSURE

From the trends shown in above plots it is clear that corrosion can be detected by ultrasonic. The trends vary with the change in frequency. Also as the area of corrosion increases there is greater fall in peak to peak voltage. Corrosion being a surface defect is better detected by 1MHz and 2MHz frequency. It was observed that there was no significant change in the signatures of 0.5MHz frequency. However if the corrosion further increases and greater amount of material is being removed then the signatures of 0.5MHz frequency may fall.

### CONCLUSIONS

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The experimental study carried out on plates with simulated notch and corrosion damage shows that the guided waves are capable of detecting these damages. Also it is possible to approximately correlate ultrasonic voltage with tensile stress of metal plates. Different frequencies were used to detect these damages and check their sensitivity towards these defects. Following conclusions are drawn from the studies done.

#### 6.1 NOTCH DEFECT STUDY

This study was done two specimens one having notch on single side and second having symmetrical notch for repeatability of experiment. Following conclusions can be drawn from this study:

- 1) This damage is detected as the peak appears when a notch is made in the specimen. So guided waves can be used for detection of surface defects.
- 2) Location of damage can be determined using  $D = \frac{VT}{2}$ , where velocity (V) of ultrasonic wave in the plate is known and time of flight (T) is obtained from the ultrasonic signature.
- 3) Magnitude of damage can be determined by the relative rise in notch echo (NE) and relative fall in back wall echo (BWE) as the percentage of damage increases.

#### 6.2 CORRELATION OF ULTRASONIC VOLTAGE WITH TENSILE STRESS

- 1) As the depth of notch increases tensile strength decreases.
- 2) As the depth of notch increases, fall in BWE voltage amplitude and decrease in tensile stress is linearly correlated.

#### 6.3 CORROSION STUDY

Uniform corrosion in the test specimen was obtained using impressed current corrosion.

- 1) As the damage due to corrosion increases, it can be detected using guided waves as there is fall in BWE voltage amplitude.

- 2) As the severity of damage increases surface becomes rough and discontinuous which result in fall in BWE voltage amplitude
- 3) 1MHz and 2MHz frequencies respond well to corrosion damage due to there surface seeking nature.
- 4) This damage is not detectable by 0.5MHz frequency because of its core seeking nature.

## SCOPE OF FUTURE STUDY

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Non destructive testing techniques are becoming quite common in nowadays in the era of industrialization and race of competition. Guided waves provide an efficient way of characterizing defects in structures. So it becomes very important to obtain reliable results from this technique and to find out better of implementing this technique.

The experimentation carried out can be extended for:

- Making localized water pond around transducers and rest of the specimen in air to gain benefits of both testing in air as well as water i.e. high speed of wave propagation in air and choice of selecting particular mode of guided wave by placing transducer in particular angle of incidence.
- Correlation between ultrasonic voltage and compressive strength for different degree of defect can be established.
- Use of guided waves can be extended to detect temperature defects i.e. creep.
- Use of guided waves can be implemented to correlate loss in strength due to fatigue so as to detect amount of fatigue in the structure.

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