CHAPTER 1

INTRODUCTION

1.1 Background of Study

Non-Destructive Test (NDT) is a testing to define and locate flaws such as cracking and corrosion within a material or a product without destroying or defacing the product. NDT usually perform during steel manufacturing process, fabrication (onshore), hook up & commissioning (offshore), operations and maintenance. There are various methods available in the industry, for example:

1. Radiographic Test (RT)
2. Ultrasonic Test (UT)
3. Dye Penetrant Test (DPT)
4. Magnetic Particle Test (MPT) and etc.

In Petronas Carigali (PCSB), the most popular methods to detect cracks and corrosion for pipeline and linepipe are Radiographic Test (RT) and Ultrasonic Test (UT). It is always recommended in Petronas Technical Standard (PTS) and the preferred NDT method depends on the criteria of the linepipe such as materials, thickness and place.

1.1.1 Ultrasonic Test

The function of Ultrasonic Test (UT) is to measure the thickness of a material or to examine the internal structure of material for possible discontinuities such as voids and cracks (Peter J. Shull, 2002). It emitted ultrasonic pulse waves (1MHz – 5MHz) from the transducer (probe) and receives the energy of pulse waves by reflection or diffraction.

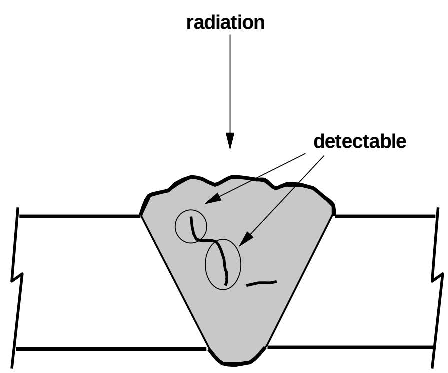
Table 1.1: Advantages and disadvantages of UT

Advantages	Disadvantages
• Internal defects can be detected and sized • Detects planar and non-planar defects • Able to pinpoint defect location • Not affected by increase in thickness • Able to access at fabrication yard, barge and platform with no hazardous • Portable  **Fig 1.1: Ultrasonic Equipment**	• No hardcopy of result available • No responsibility if any false decision occurs (in Petronas) – there is no proof for error because crack can occur after inspection. • Surface must be smooth and need to use couplant • Not really required by PTS unless there are certain condition such as thickness and materials • For flaw detection of welds: ⇒ Normally not suitable for surface and near surface defect detection (dead zone) ⇒ Normally not suitable for wall thickness < 8mm (practically) or < 5mm (theoretically)

1.1.2 Radiographic Test

The function of Radiographic Test (RT) is to detect material defects, structural discontinuities, mechanical failures and assembly errors using a visual image on the interior of materials or non-accessible areas (Peter J. Shull, 2002). It uses the ability of short wavelength electromagnetic radiation (high energy photons) to penetrate various materials. It consists of radiation source and radiographic film.

Table 1.2: Advantages and disadvantages using RT

Advantages	Disadvantages
• Detect discontinuity of entire test piece thickness • Permanent record film • Good for detecting non-planar defects 3D: slag inclusion, porosity • Shows defects in a plan view (2-Dimension)  **Fig 1.2: RT can detect non planar defects**	• Radiation hazard and require a safety wall and no suitable during at fabrication yard, barge and platform • Limited by material thickness • Not good for detecting planar defects (must be parallel to the radiation beam to be detected clearly) • Does not indicate defect depth • Correct choice of radiation energy or exposure time is a critical factor.

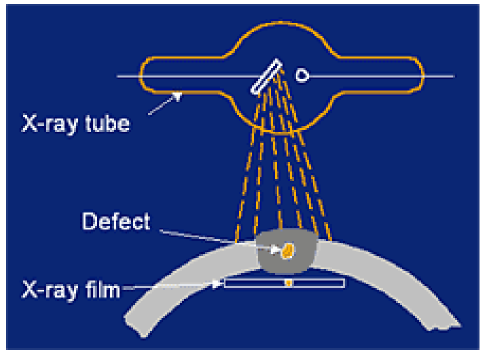


Fig 1.3: Radiographic Inspection

1.2 Problem Statement

1.2.1 Problem Definition

For linepipe inspection, PTS requires to perform RT or UT and it depends on the materials, thickness and space. But there are certain limitations especially during linepipe inspection especially at fabrication yard, on the barge and at the platform. Below are the problems identified:

Table 1.3: Problem identified on linepipe inspection

Problems	Description	Normal	Heavy Wall Thickness (HWT)
The inspection rate did not cope with the production rate	Diameter	Less than 2 inch	More than 2 inch
	Production Rate (weldment/day)	75	60
	Inspection rate (test/night)	25-30	10
The safety distance require due to safety issues	Energy (RT Source)	Iridium 192	
	Safety Distance (max allowable 25 Curie) SD = Curies x radioactivity x 1000 / 7.5	126.49m	

For all cases, the production rate is high but the testing rate did not cope with the testing rate. As we can see in the normal cases, where the production rate is 75 weldments per day but the testing rate is only up to 30 testing per night. RT has a certain safety distance and all works nearby must be stopped. They perform RT at night so they do not disturb other works. They normally have only one RT groups due to constraint of spaces and the maximum allowable is only two groups. At yard, the time is very restraint and each works must be completed in certain period of time. Due to this, there is a chance for the engineers to make a wrong judgment. For any delay, it will increase the cost. Based on interview, for a full facility pipeline installation barge, the rental will cost up to RM 1 million per day. There are many over schedule projects occurred in Petronas and they are wasting the money due to time delay.

For the heavy wall thickness (HWT) cases, usually high radiation level (Curie) will be used. The thickness of HWT pipe is depends on its materials. If low Curie is used on HWT, the time taken for shooting the image will increase but if high Curie is used, then is more hazardous and requires more safety distances. For safety purposes, PTS allowed only up to 25 Curie at fabrication yard. The engineers or operators must decide the preferable Curie level to be used.

1.2.2 Significant of the Project

This project is benefit to Petronas because in term of safety, cost, time and quality, Petronas can save a large amount of money when the problem is overcome. Petronas always facing a problem when performing linepipe inspection especially at fabrication yard and on the barge. Rather than RT and UT, there is another method that will more suitable due to the current technology availability for linepipe inspection.

Petronas may lose a huge amount of money due to linepipe inspection delay. The works cannot be continue when the linepipe are not inspected. It is a very important to avoid any damage or cracks after installation. If there are any cracks after installation, then it may lead to hazardous environment and can cause leaking into the sea or sometime can cause explosion because the pressure use inside the pipeline is very high. The cost for repairing after installation may very high compare to standard price.

The study is significant to search for other alternatives of NDT methods that can replace RT by considering the costs, time, quality and safety. For that reasons, we need to understand the behaviours of the preferable alternatives method.

1.3 Objective & Scope of Study

The objective of this project is to find an alternative of NTD methods that can increase the inspection rate to reduce the gap between production rate and inspection rate for carbon steel linepipe inspection. Safety measure must be considered to avoid any injury and expose to radioactivity.

In PTS, almost all of the parts and steps in developing a platform must perform NDT. It is to make sure that the reliability and safety of each structure. It is include in:

i. Piping
ii. Structural Pipeline
iii. Linepipe
iv. Boilers
v. Vessel
vi. Tank

* Linepipe has been selected for this project and the area covered during hook up and installation.

For this project, generally the scopes of works are:

i. Understudy of available NDT methods

There are many NDT techniques available in the market such as Magnetic Particle Test, Dye Penetrant Test, X-Ray and more. Also, there are an advanced technique of NDT which are Time of Flight Diffraction (ToFD), Auto UT, Phased Array and many more. They have their advantages and limitations due to the purpose of inspection. All of this advanced technique need to be understudy to select the suitable method for linepipe inspection at fabrication yard and on the barge.

ii. Laboratory Test

The laboratory test has been conducted at SIRIM, Shah Alam once the machine is available there. The test has been focused on the reliability of phased array on a carbon steel material at the weldments. The time also been recorded to estimate the time reduce for linepipe inspection. The result has been analyzed and compared with the theoretical.

iii. Communicate the findings

The findings have been reported to the supervisor weekly and final report has been compiled and submitted at the end of the period.

CHAPTER 2

LITERATURE REVIEW & THEORY

2.1 Linepipe Manufacturing and Installation

2.1.1 Linepipe Manufacturing and Installation

Appendices 1 (PTS 20.107) show the linepipe fabrication begins at the mill fabrication where it undergoes into several processes such as transport, constructing, pre-commissioning and commissioning. Commissioning is a process where they installed the linepipe into a pipeline. The conventional method for installing offshore pipelines in relatively shallow water is commonly referred to as the S-Lay method because the profile of the pipe as it moves in a horizontal plane from the welding and inspection stations on the lay barge across the stern of the lay barge and onto the ocean floor forms an elongated “S.” (http://www.globalsecurity.org/military/systems/ship/offshore-pipelaying.htm).

As the pipeline moves across the stern of the lay barge and before it reaches the ocean floor, the pipe is supported by a truss-like circular structure equipped with rollers and known as a stinger. The purpose of the stinger in the S-lay configuration is to control the deflection of the pipe in the over-bend region above the pipeline inflection point in order to return the angle of the pipeline at the surface to the horizontal. The curvature radius of the stinger corresponds to at least the maximum bending stress. To avoid a bending moment peak at the last roller, the pipe must lift off smoothly from the stinger well ahead of the lower end of the stinger.

In extremely deep water the angle of the pipe becomes so steep that the required stinger length may not be feasible. Deeper water depths will result in a steeper lift-off angle of the suspended pipe span at the stinger tip. This will require the stinger to be longer and more curved to accommodate the greater arc of reverse curvature in the overbend region. Accordingly, greater stinger buoyancy and structural strength will be necessary to support the increased weight of the suspended pipe span. The practical water depth limit for a large, conventionally moored lay barge that uses the S-lay method is about 1,000 ft, based on a ratio of anchor line length to water depth of about five to one.

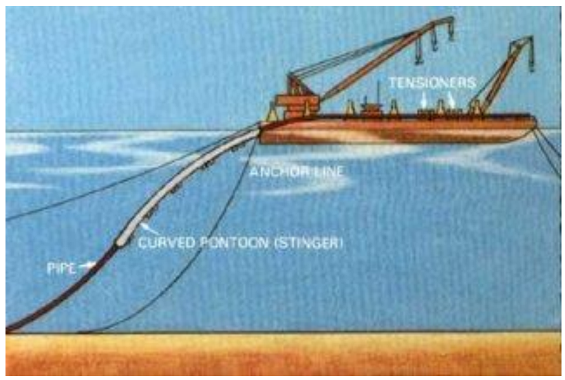


Fig 2.1: S-Lay linepipe illustration (Left) and the linepipe move into the stinger

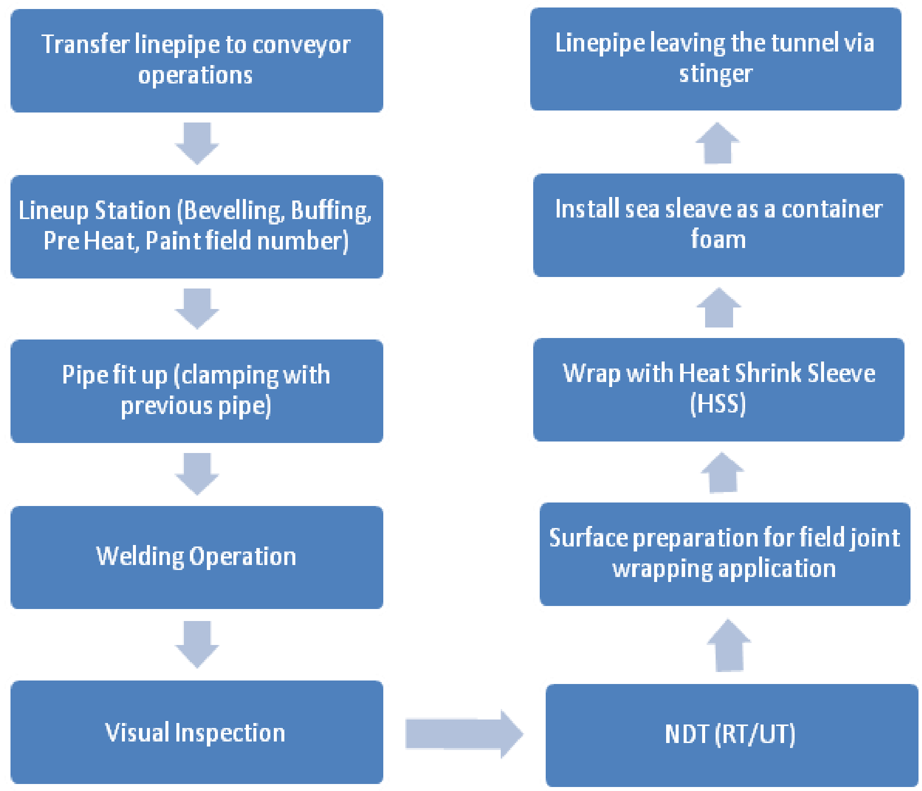


Fig 2.2: S-Lay Linepipe Installation Process

1st step:

Transferring linepipe to conveyor operations. A process where it move the linepipe into a tunnel to align with a previous linepipe.

2nd step:

This is the lineup station where pipeline preparation for welding operations takes place. Activities such as beveling, buffing and pre-heat treatment. Here also where riggers paint the field joint numbers for linepipe identification number.

3rd step:

Pipe Fit up. The red equipment call internal line up clamp is used to clamp the previous linepipe with a new one before welding. It makes the welding process become easier and make the linepipe stay in its position. Any large amount of vibration may lead to error in dimension and crack distribution.

4th step:

Welding operation by using an auto weld machine. Normally, this is the pipe ramp activity arrangement for an automatic welding;

Station 1: Welding Root and Hot Pass

Station 2: Welding Fill

Station 3: Welding Fill

Station 4: Capping, Visual Inspection and Touch Up Weld

Station 5: Touch-up Weld, Repair and Radiographic Inspection

Station 6: Repair and Radiographic Inspection

Station 7: Field Joint Cleaning & Tape Wrap application.

5th step:

Visual inspection to ensure the final welding was clear & cleaned from weld splatter & ready for NDT.

6th step:

Non Destructive Test (NDT) to check for welding quality & ensure no defect by using RT.

7th step:

The preparation stage for field joint wrapping application.

8th step:

Riggers complete wrapping HSS (Heat Shrink Sleeve) & heat the HSS to ensure it is stick to the field joint surface.

9th step:

Riggers installing sea sleeve as a container for foam. Foam injection in progress.

10th step:

The pipeline leaving the tunnel via stinger. The whole process beginning again until the end of operations.

2.2 Wave Front Formation

While a single element transducer may be thought of as a piston source, a single disk or plate pushing forward on the test medium, the wave it generates may be mathematically modeled as the sum of the waves from a very large number of point sources. This derives from Huygens' Principle, first proposed by seventeenth-century Dutch physicist Christiaan Huygens, which states that each point on an advancing wavefront may be thought of as a point source that launches a new spherical wave, and that the resulting unified wave front is the sum of all of these individual spherical waves (Don. E. Bray & Roderic K. Stanley, 1997).

2.2.1 Beam spreading

In principle, the sound wave generated by a transducer will travel in a straight line until it encounters a material boundary. What happens then is discussed below. But if the sound path length is longer than the near field distance, the beam will also increase in diameter, diverging like the beam of a spotlight. The beam spread angle of an unfocused transducer can be calculated as follows:

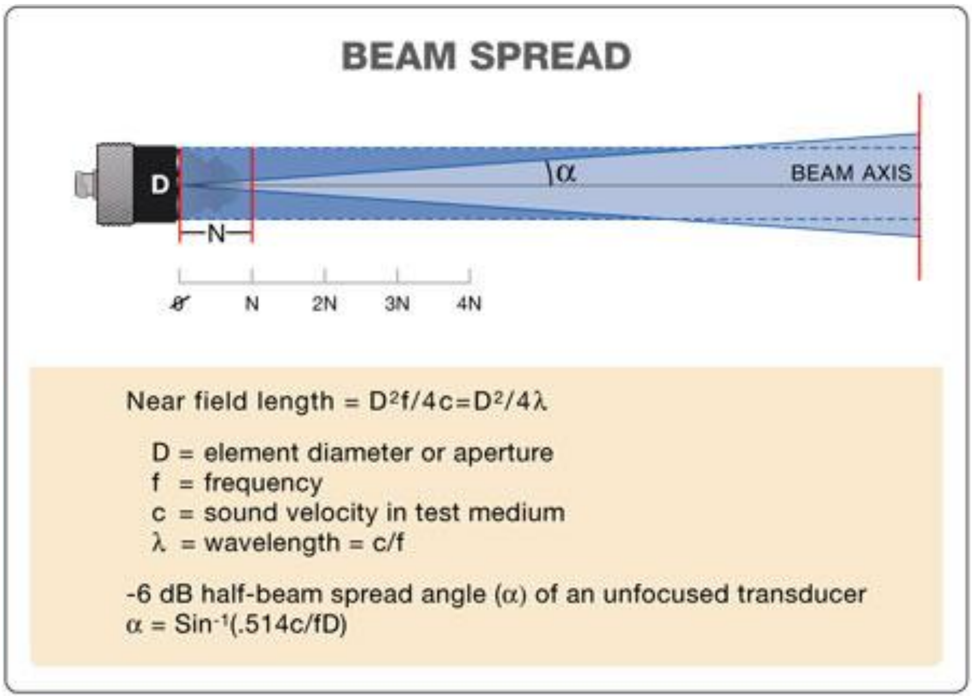


Fig 2.3: Beam Spread equation to find the Near Field Length

From this equation it can be seen that beam spreading increases with lower frequencies and smaller diameters. Since a large beam spread angle can cause sound energy per unit area to quickly drop with distance, effectively decreasing sensitivity to small reflectors, echo response in some applications involving long sound paths can be improved by using higher frequency and/or larger diameter transducer.

2.2.2 Attenuation

As it travels through a medium, the organized wave front generated by an ultrasonic transducer will begin to break down due to imperfect transmission of energy through the microstructure of any material. Organized mechanical vibrations (sound waves) turn into random mechanical vibrations (heat) until the wave front is no longer detectable. This process is known as sound attenuation (Don. E. Bray & Roderic K. Stanley, 1997).

The mathematical theory of attenuation and scattering is complex. The loss of amplitude due to attenuation across a given sound path will be the sum of absorption effects, which increase linearly with frequency, and scattering effects, which vary through three zones depending on the ratio of the size of grain boundaries or other scatterers to wavelength. In all cases, scattering effects increase with frequency. For a given material at a given temperature, tested at a given frequency, there will be a specific attenuation coefficient, commonly expressed in Nepers per centimeter (Np/cm). Once this attenuation coefficient is known, losses across a given sound path may be calculated according to the equation:

$$p = p_0 e^{-\alpha d}$$

Where
p = sound pressure at end of path
p_0 = sound pressure at beginning of path
e = base of natural logarithm
a = attenuation coefficient
d = sound path length

Fig 2.4: Equation for the attenuation

As a practical matter, in ultrasonic NDT applications attenuation coefficients are normally measured rather than calculated. Higher frequencies will be attenuated more rapidly than lower frequencies in any medium, so low test frequencies are usually employed in materials with high attenuation coefficients like low density plastics and rubber.

2.2.3 Reflection and transmission at a perpendicular plane boundary

When a sound wave traveling through a medium encounters a boundary with a dissimilar medium that lies perpendicular to the direction of the wave, a portion of the wave energy will be reflected straight back and a portion will continue straight ahead. The percentage of reflection versus transmission is related to the relative acoustic impedances of the two materials, with acoustic impedance in turn being defined as material density multiplied by speed of sound (Don. E. Bray & Roderic K. Stanley, 1997). The reflection coefficient at a planar boundary, the percentage of sound energy that is reflected back to the source, may be calculated as follows:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Where
R = reflection coefficient in percent
Z_1 = acoustic impedance of first medium
Z_2 = acoustic impedance of second medium

Fig 2.5: Equation to find the reflection coefficient in percent

From this equation it can be seen that as the acoustic impedances of the two materials become more similar, the reflection coefficient decreases, and as the acoustic impedances become less similar, the reflection coefficient increases. In theory the reflection from the boundary between two materials of the same acoustic impedance is zero, while in the case of materials with very dissimilar acoustic impedances, as in a boundary between steel and air, the reflection coefficient approaches 100%.

2.2.4 Refraction and mode conversion at non-perpendicular boundaries

When a sound wave traveling through a material encounters a boundary with a different material at an angle other than zero degrees, a portion of the wave energy will be reflected forward at an angle equal to the angle of incidence. At the same time, the portion of the wave energy that is transmitted into the second material will be refracted in accordance with Snell's Law, which was independently derived by at least two seventeenth-century mathematicians (Don. E. Bray & Roderic K. Stanley, 1997). Snell's law related the sines of the incident and refracted angle to the wave velocity in each material as diagramed below:

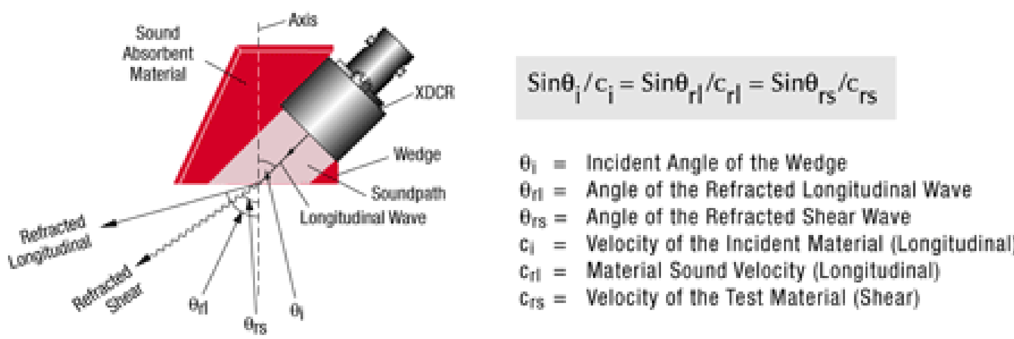


Fig 2.6: Equation to find the incident angle

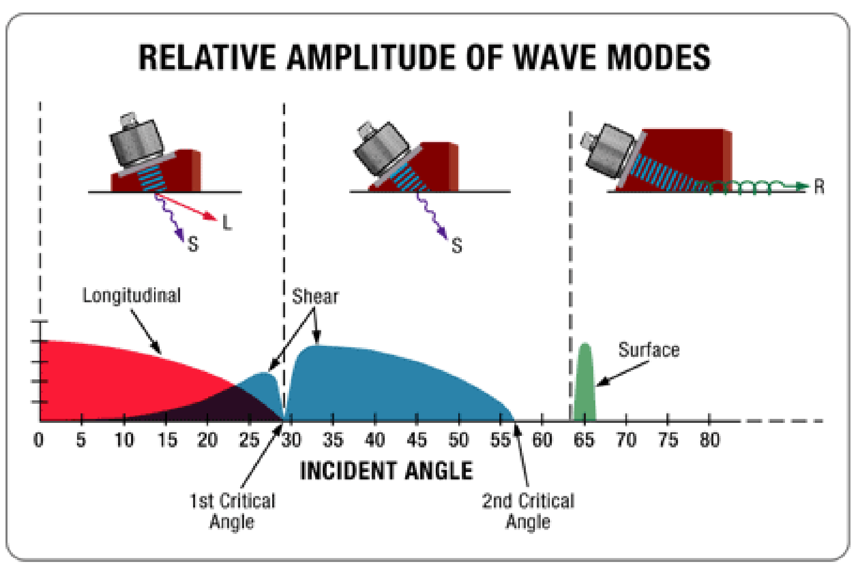


Fig 2.7: Relative Amplitude of Wave Modes (Longitudinal, Shear and Surface Waves)

If sound velocity in the second medium is higher than that in the first, then above certain angles this bending will be accompanied by mode conversion, most commonly from a longitudinal wave mode to a shear wave mode. This is the basis of widely used angle beam inspection techniques. As the incident angle in the first (slower) medium such as a wedge or water increases, the angle of the refracted longitudinal wave in the second (faster) material such as metal will increase. As the refracted longitudinal wave angle approaches 90 degrees, a progressively greater portion of the wave energy will be converted to a lower velocity shear wave that will be refracted at the angle predicted by Snell's Law.

At incident angles higher than that which would create a 90 degree refracted longitudinal wave, the refracted wave exists entirely in shear mode. A still higher incident angle will result in a situation where the shear wave is theoretically refracted at 90 degrees, at which point a surface wave is generated in the second material. The diagram below shows this effect for a typical angle beam assembly coupled into steel.

2.3 Phased Array

Phased Array Technology (PA) ultrasonic testing is the computer-controlled excitation (amplitude and delay) of individual elements in a multielement probe. The excitation of multiple piezocomposite elements can generate a focused ultrasonic beam with the possibility of dynamically modifying beam parameters such as angle, focal distance and focal spot size through software.

Phased array ultrasound has emerged as a rapid non-destructive evaluation technique for the detection and imaging of crack-like defects in structural components due to the flexibility it offers in varying the angle of inspection and focusing of the beam to a point of interest. The principle of phased array ultrasonic beam generation is based on the use of individual transducer elements that can each be independently driven with controlled phase delays of excitation.

Using this phase delay, the parameters of the ultrasonic beam, such as the depth of focus and the beam angle can be varied while the testing is being carried out. This results in an improved capability to image defects located in regions even with limited accessibility. Using the linear scanning capability of the phased array, the manual or automated motion of the ultrasonic probe during flaw detection is replaced by the near-real-time electronic scanning.

2.3.1 Phased array advantages

i. Software control of beam angle, focal distance, and spot size
ii. Multiple-angle inspection with a single, small, electronically-controlled multielement probe
iii. Greater flexibility for the inspection of complex geometry
iv. High-speed scans with no moving parts

Fig 2.8: PA control system

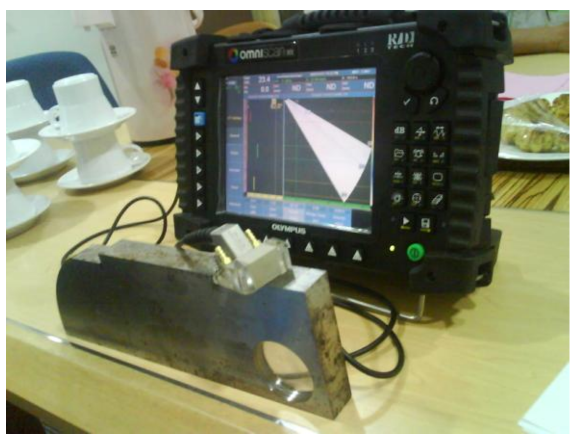


Fig 2.9: PA machine with a probe on a calibration block

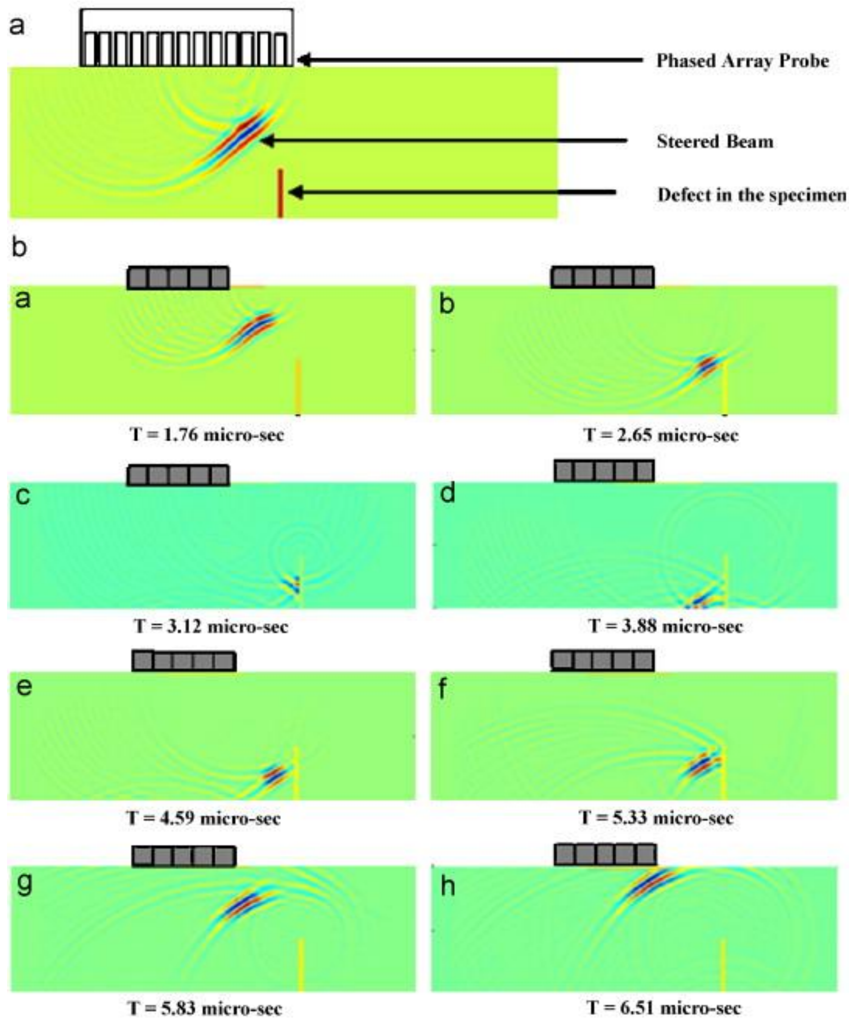
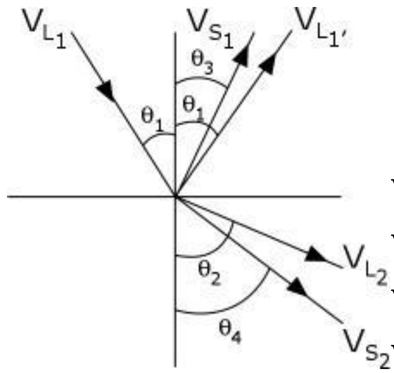


Fig. 2.10: Beam steering and focusing in a phased array transducer. (b) Interaction of a phase steered wave with the crack tip and corner.

2.3.2 Longitudinal and Transverse Wave

In solids, sound waves can propagate in four principle modes that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves and in thin materials as plate waves. Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing.



$$\frac{\sin\theta_1}{V_{L_1}} = \frac{\sin\theta_2}{V_{L_2}} = \frac{\sin\theta_3}{V_{S_1}} = \frac{\sin\theta_4}{V_{S_2}}$$

$\mathbf{V_{L1}}$ is the longitudinal wave velocity in material 1.
$\mathbf{V_{L2}}$ is the longitudinal wave velocity in material 2.
$\mathbf{V_{S1}}$ is the shear wave velocity in material 1.
$\mathbf{V_{S2}}$ is the shear wave velocity in material 2.

Notice that the shear wave (V_{S2}) is not refracted as much as the longitudinal wave (V_{L2}). This occurs because shear waves travel around 50% slower than longitudinal waves. Therefore, the velocity difference between the incident longitudinal wave and the shear wave is not as great as it is between the incident and refracted longitudinal waves. Notes also that the direction of longitudinal wave is compressional along the horizontal line but the direction of shear wave is upside down (sine). That's why shear wave is slower than longitudinal wave. In fact, shear waves are usually generated in materials using some of the energy from longitudinal waves (Robert E. Green, 1999).

	Longitudinal (m/s)	**Transverse (m/s)**
Air	330	-
Water	1430	-
Carbon Steel	5900	3245
Stainless Steel	5640	3070
Cast Iron	3500-5600	2200-3200
Aluminum	6320	3130
Brass	4280	2030

Table 2.1: Longitudinal and Transverse Wave Velocity

2.3.3 Constructive and Destructive Wave

Whenever waves originating from two or more sources interact with each other, there will be phasing effects leading to an increase or decrease in wave energy at the point of combination. When elastic waves of the same frequency meet in such a way that their displacements are precisely synchronized (in phase, or 0 degree phase angle), the wave energies will add together to create a larger amplitude wave. If they meet in such a way that their displacements are exactly opposite (180 degrees out of phase), then the wave energies will cancel each other. At phase angles between 0 degrees and 180 degrees, there will be a range of intermediate stages between full addition and full cancellation. By varying the timing of the waves from a large number of sources, it is possible to use these effects to both steer and focus the resulting combined wave front. This is an essential principle behind phased array testing (C. Clay, Shi-Chang Wooh, Lawrence Azar, and Ji-Yong Wang, 1999).

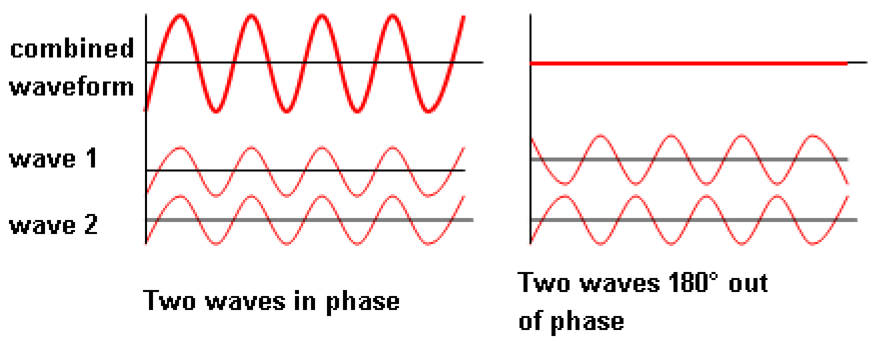


Fig 2.11: Constructive and Destructive Waves

In conventional transducers, constructive and destructive interference effects create the near field and far field zones and the various pressure gradients therein. Additionally, a conventional angle beam transducer uses a single element to launch a wave in a wedge. Points on this wave front experience different delay intervals due to the shape of the wedge. These are mechanical delays, as opposed to the electronic delays employed in phased array testing. When the wave front hits the bottom surface it can be visualized through Huygens's Principle as a series of point sources. The theoretically spherical waves from each of these points interact to form a single wave from at an angle determined by Snell's Law.

In phased array testing, the predictable reinforcement and cancellation effects caused by phasing are used to shape and steer the ultrasonic beam. Pulsing individual elements or groups of elements with different delays creates a series of point source waves that will combine into a single wave front that will travel at a selected angle. This electronic effect is similar to the mechanical delay generated by a conventional wedge, but it can be further steered by changing the pattern of delays. Through constructive interference, the amplitude of this combined wave can be considerably greater than the amplitude of any one of the individual waves that produce it. Similarly, variable delays are applied to the echoes received by each element of the array to sum the responses in such a way as to represent a single angular and focal component of the total beam. In addition to altering the direction of the primary wave front, this combination of individual beam components allows beam focusing at any point in the near field.

The returning echoes are received by the various elements or groups of elements and time-shifted as necessary to compensate for varying wedge delays and then summed. Unlike a conventional single element transducer, which will effectively merge the effects of all beam components that strike its area, a phased array transducer can spatially sort the returning wavefront according to the arrival time and amplitude at each element. When processed by instrument software, each returned focal law represents the reflection from a particular angular component of the beam, a particular point along a linear path, and/or a reflection from a particular focal depth. The echo information can then be displayed in any of several standard formats.

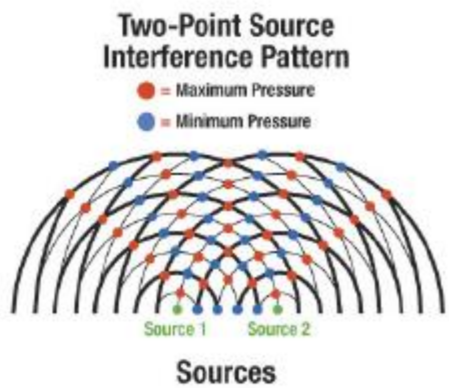


Fig 2.12: Two Point Source Interference Pattern

Compared to conventional wave forming, the acoustic beam in the probe is generated by the Huygens principles. An angled probe introduces appropriate delays during emission to generate an angle beam. Such as 60° probe, the acoustic beam is generated by many sources and the angle will be adjusted due to delay of each source.

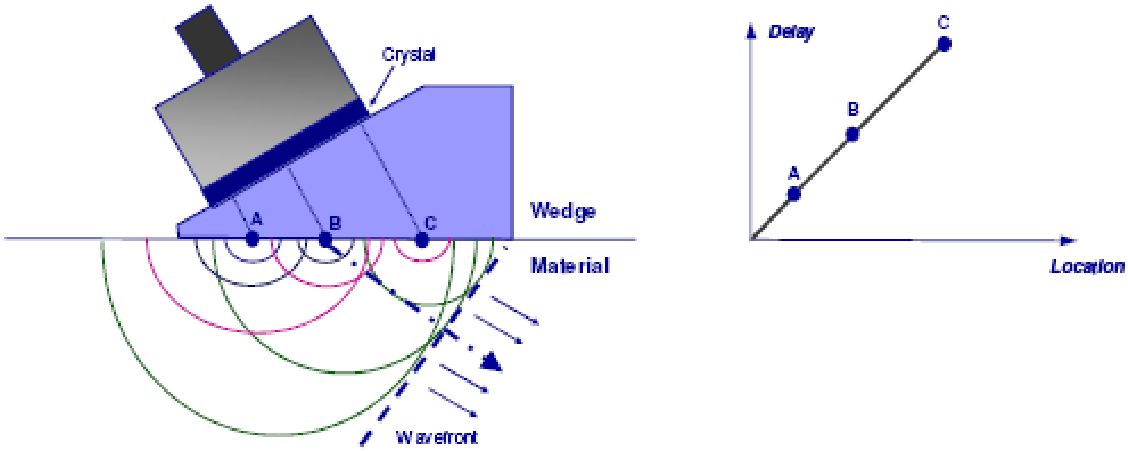


Fig 2.13: The delay control the angle of wavefront

Angled probe also introduces delays during reception, so that only waves "in phase" yield constructive interference on the crystal.

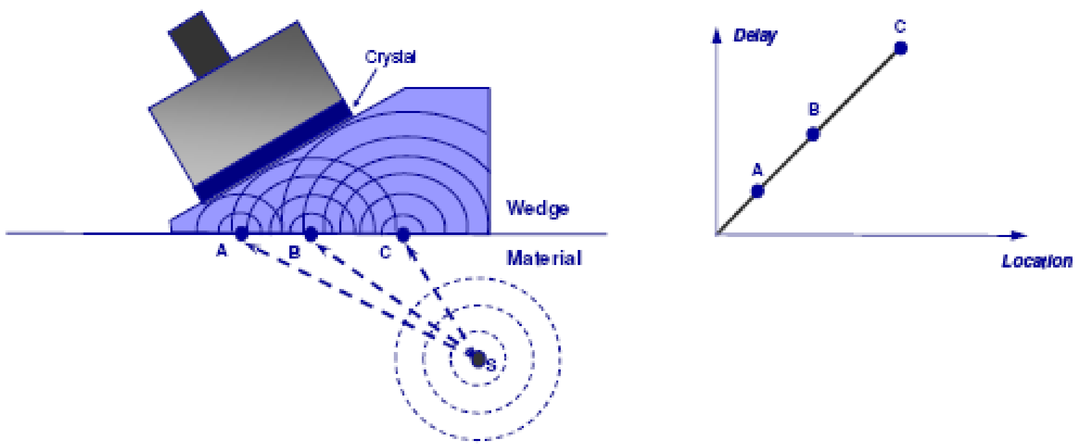


Fig 2.14: The reflection waves gives a signal back to the probe and detected by the crystal

2.3.4 Phased Array Waves Forming

PA wave forming also is based on Huygens principle where appropriate delays are introduced electronically during emission to generate the angle beam (http://www.olympus-ims.com/en/).

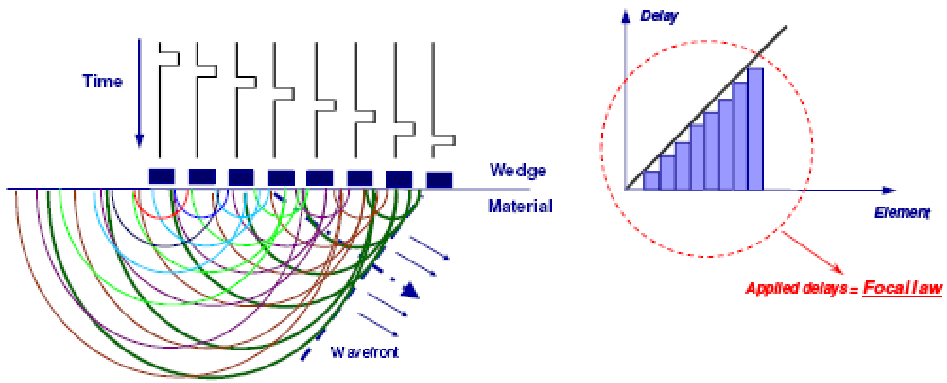


Fig 2.15: The element control the wave front

During reception, only signals satisfying the delay law shall be in phase and generate significant signal after summation.

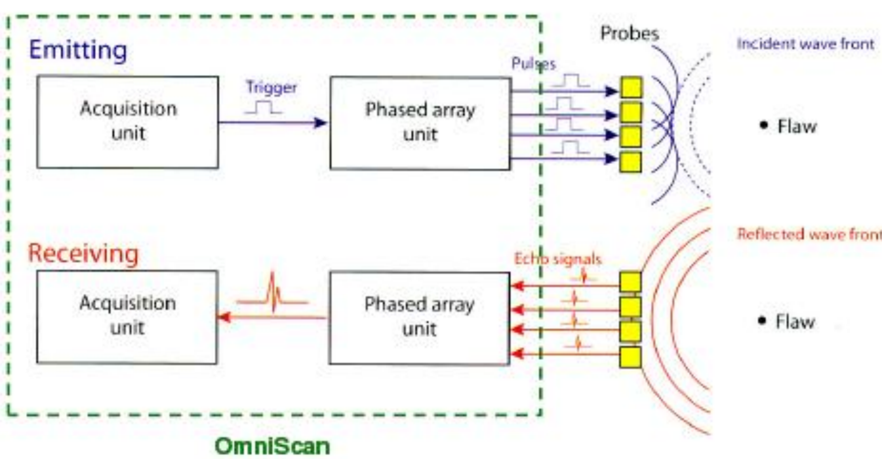
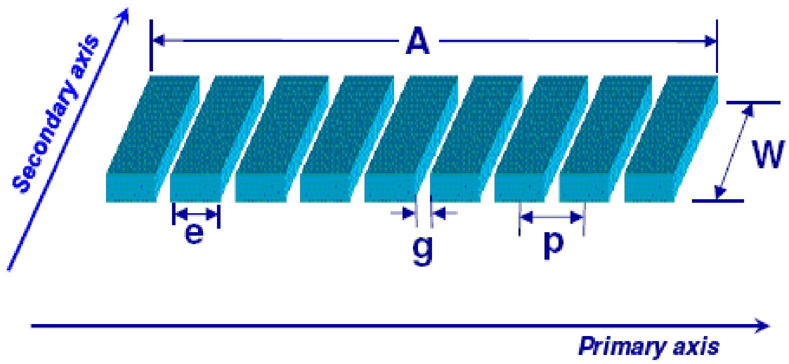


Fig 2.16: The reflection pulse detected and receives in an echo signals (sine waves)

2.3.5 Design Parameters of PA Probes

Basically, for linear array it consists of a long conventional probe (wedge) but for PA probes, they cut in small elements up until 128 elements in a single probe that can be individually excited (Don. E. Bray & Don McBride). The higher the amount of elements, better image will occur at the screen.



***f*:** Frequency

λ: Wavelength

n: Total number of elements in array

p: Pitch, center-to-center distance between two successive elements

A: Total aperture in steering direction (Primary axis)

Where, **A** = **p** × number of element used to generate the beam

W: Width, aperture in passive direction (Secondary axis)

e: Width of an individual element

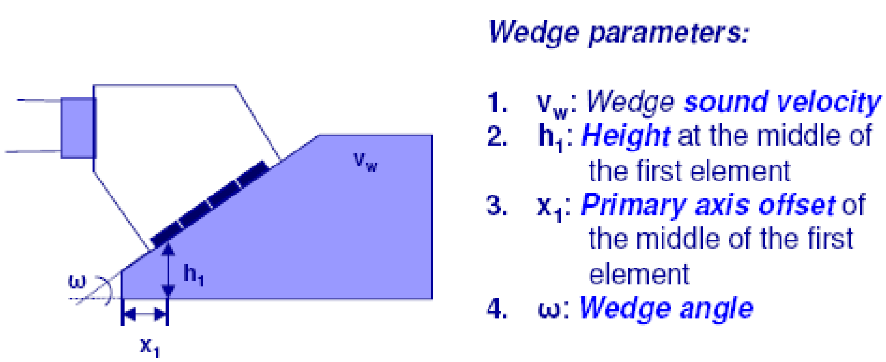


Fig 2.17: Wedge parameters

Table 2.2: Factor that effect the waves

Factor that effect waves	Effect
Probe Frequency	i. Higher frequencies and larger apertures may provide better signal or noise which means tighter and optimized focal spot
Element width (e)	ii. As the element width decrease: iii. Beam steering capability (angle range) increase iv. Number of elements increase rapidly v. The sharpness of the images is reduced
Number of elements (n)	vi. Number of elements is a compromise between: vii. Desired physical coverage of the prove and sensitivity viii. Focusing capability ix. Steering capability x. Electronic system capability xi. Cost
Pitch (p)	xii. Number of source is typically 16 xiii. Maximum aperture (A max) = Pitch (p) x 16 xiv. For a high steering range, p must be small xv. For a good sensitivity, the A must be large because it provides a large Near Zone distance (good focusing coefficient)

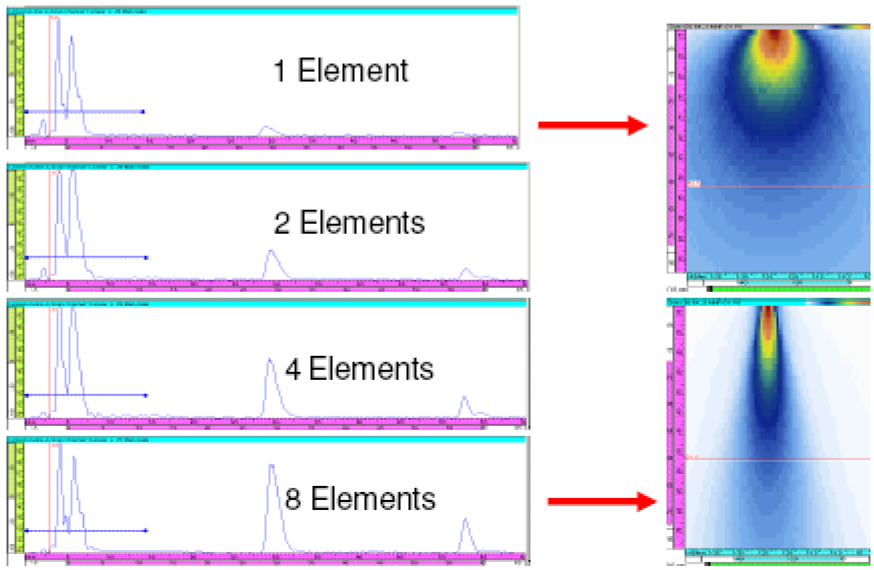
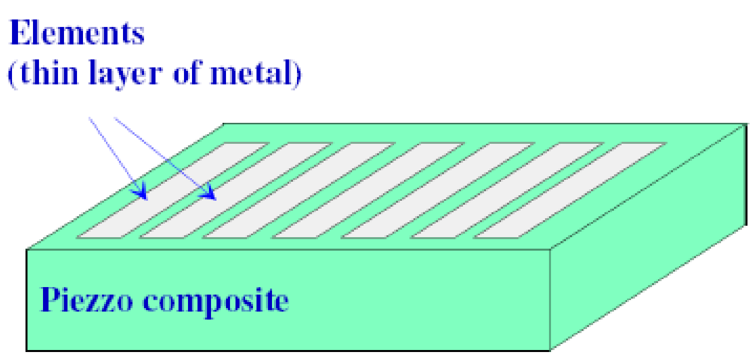


Fig 2.18: The number of elements provides the focal point of the image

2.3.6 PA Probes Manufacturing

For standard probes, it consists of a metallic layer where it deposited on the piezo-composite. This metallic layer conforms to the element pattern and provides electrical contacts for each element. The probe construction is similar to a conventional probe (Lester W. Schmerr Jr, Iowa University).



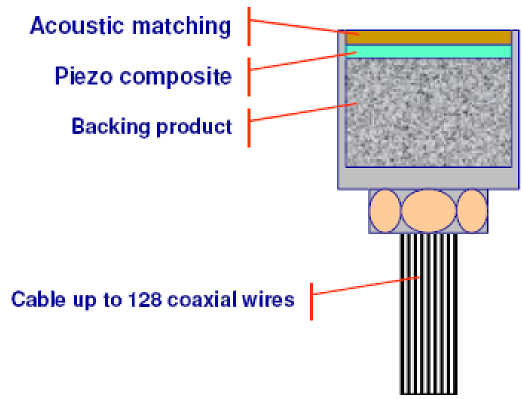


Fig 2.19: Piezo composite probe consists up to 128 elements

2.3.7 Scanning Patterns (http://www.olympus-ims.com/en/)

i. Electronic Linear Scanning

a. A single focal law is multiplexed across a group of active elements; scanning is performed at a constant angle and along the phased array probe length (aperture).

b. This is equivalent to a conventional ultrasonic transducer performing a raster scan for corrosion mapping or shear-wave inspection.

c. If an angle wave is used, the focal laws compensate for different time delays inside the wedge.

ii. Sectorial Scanning

a. It is also called azimuthal or angular scanning.

b. The beam is moved through a sweep range for a specific local depth may be added. The angular sectors may have different values.

iii. Dynamic Depth Focusing (DDF)

a. It is programmable, real time array response-on-reception accomplished by modifying the delay, gain and excitation of each element as a function of time.
b. DDF replaces multiple focal laws for the same focal range created by the emitted beam wit separate "Focused beams" at the receiving stage. In other words, DDF dynamically changes the focal distance as the signal returns to the phased array prove.
c. DDF significantly increases the depth of field and signal-to-noise ratio.

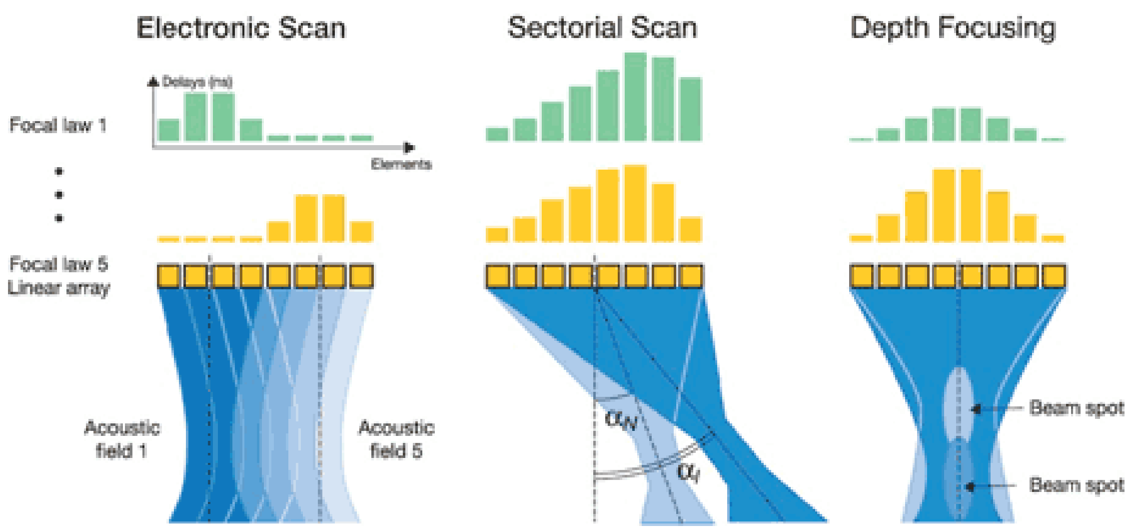


Fig 2.20: Concept for generation of linear and sectorial scans using phased arrays

2.3.8 Beam Steering

The essence of phased array testing is an ultrasonic beam whose direction (refracted angle) and focus can be steered electronically by varying the excitation delay of individual elements or groups of elements (http://www.olympus-ims.com/en/). This beam steering permits multiple angles and multiple point inspection from a single probe and a single probe position.

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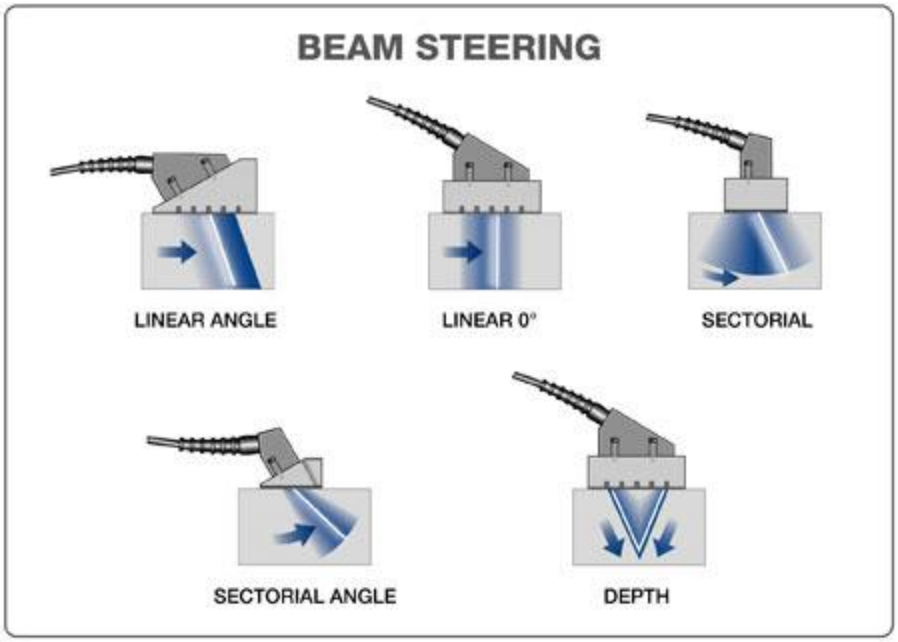


Fig 2.21: Type of beam steering

Ultrasonic beam characteristics are defined by many factors. In addition to element dimension, frequency and damping that govern conventional single element performance, phased array transducers behavior is affected by how smaller individual elements are positioned, sized and grouped to create an effective aperture equivalent to its conventional counterpart.

For phased array transducers N elements are grouped together to form the effective aperture for which beam spread can be approximated by conventional transducer models.

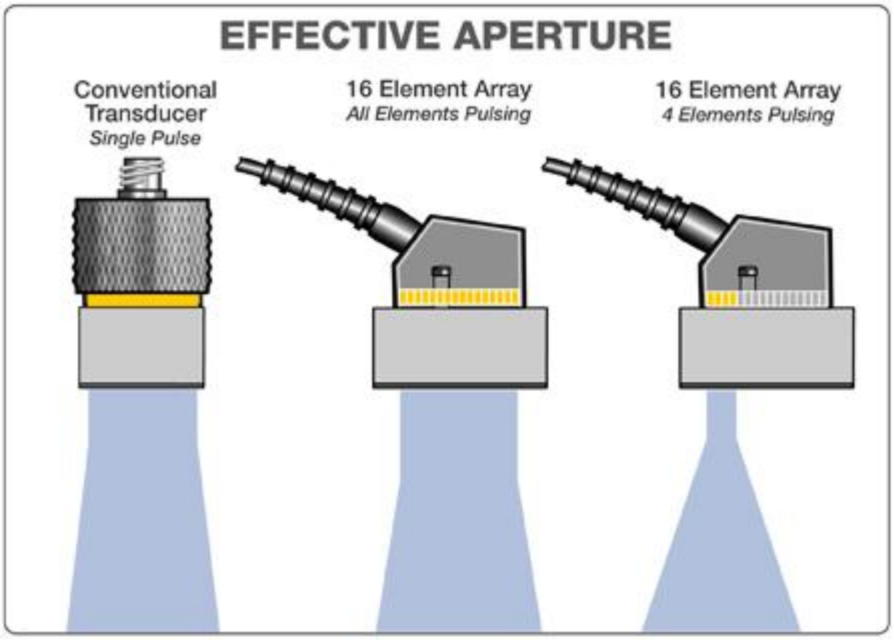


Fig 2.22: Effective aperture

For phased array transducers, the maximum steering angle (at -6 dB) in a given case is derived from the beam spread equation. It can be easily seen that small elements have more beam spreading and hence higher angular energy content, which can be combined to maximize steering. As element size decreases, more elements must be pulsed together to maintain sensitivity.

$$\sin \theta_{st} = 0.514 \frac{\lambda}{e}$$

Where
$\sin \theta_{st}$ = sine of the maximum steeting angle
λ = wavelength in test material
e = element width

Fig 2.23: Maximum steering angle equation

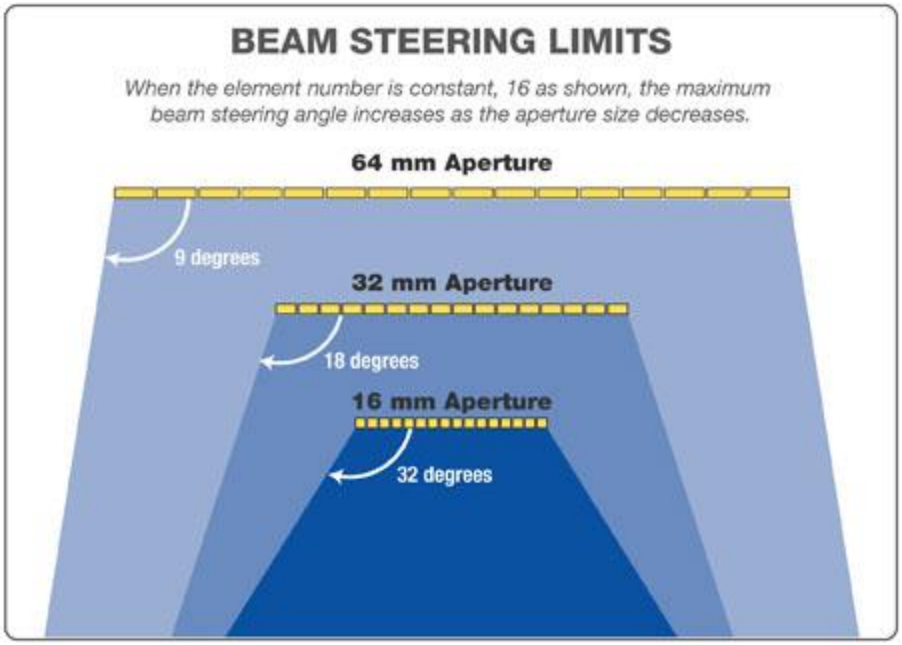


Fig 2.24: Comparison between the apertures

The practical limit for phased array transducer manufacturing restricts the smallest individual element width to 0.2 mm, the active aperture for a 16 element probe with 0.2 mm elements would be 3.2 mm. Creating an aperture of 6.4 mm would require 32 elements. While these transducers would no doubt maximize steering, the small apertures would limit static coverage area, sensitivity, and focusing ability.

The steering range can be further modified by using an angled wedge to change the incident angle of the sound beam independently of electronic steering.

2.3.9 Beam Focusing

From the beam spread angle, the beam diameter at any distance from the transducer can be calculated. In the case of a square or rectangular phased array transducer, beam spreading in the passive plane will be similar to that of an unfocused transducer. In the steered or active plane, the beam can be electronically focused to converge acoustic energy at a desired depth. With a focused transducer, the beam profile can typically be represented by a tapering cone (or wedge in the case of single-axis focusing) that converges to a focal point and then diverges at an equal angle beyond the focal point.

The near field length and hence the natural divergence of an ultrasonic beam are determined by aperture (equal to element diameter in the case of conventional monolithic transducers) and wavelength (wave velocity divided by frequency). For an unfocused transducer, the near field length, beam spread angle, and beam diameter can be calculated as follows (http://www.olympus-ims.com/en/):

Near field length = $D^2 f / 4c = D^2 / 4\lambda$

where D = element diameter or aperture
f = frequency
c = sound velocity in test medium
λ = wavelength = c/f

Fig 2.25: Near Field Length

The near field length in a given material also defines the maximum depth at which a sound beam can be focused. A beam cannot be focused beyond the end of the near field.

A focused transducer's effective sensitivity is affected by the beam diameter at the point of interest. The smaller the beam diameter, the greater will be the amount of energy that will be reflected by a small flaw. The -6 dB beam diameter of a focused transducer at the focal point can be calculated as follows:

-6 dB beam diameter = 1.02Fc/fD where F = focal length in test medium

Fig 2.26: Beam diameter

From these formulas it can be seen that as the element diameter and/or frequency increase, the beam spread angle decreases. A smaller beam spread angle in turn can result in higher effective sensitivity in the far field zone since the beam energy dissipates more slowly. Within its near field, a transducer can be focused to create a beam the converges rather than diverges. Narrowing the beam diameter to a focal point increases sound energy per unit area within the focal zone and thus increasing sensitivity to small reflectors. Conventional transducers usually do this with a refractive acoustic lens, while phased arrays do it electronically by means of phased pulsing and the resulting beam shaping effects.

In the case of the most commonly used linear and square phased arrays with rectangular elements, the beam will be focused in the steering direction and unfocused in the passive direction. Increasing the aperture size increases the sharpness of the focused beam, as can be seen in these beam profiles. Red areas correspond to the highest sound pressure, and blue areas to lower sound pressure.

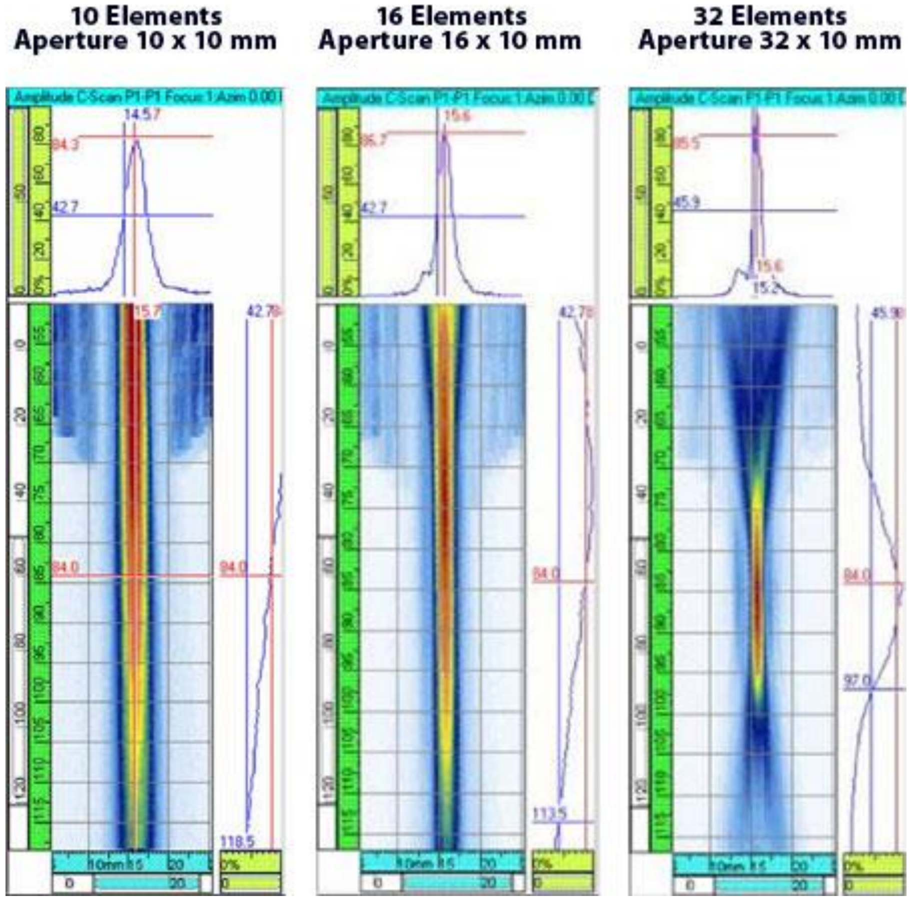


Fig 2.27: Difference between the elements and aperture

CHAPTER 3

METHODOLOGY & PROJECT WORK

3.1 Project Flow

The flow of the project is shown in the figure 3.1, the first stage is to gather information about all NDT techniques available, find the problems and objectives. The information has been gathered from books, journals, interviews and others relevant material.

Second stage is list all the advanced technique and makes the comparison based on theoretical criteria. The preferred alternative was selected and all the data or information regarding phased array has been studied. Several tests were conducted to meet the criteria for linepipe inspection. The analysis has been done and the objectives were achieved.

The final stage is to compile the results and produce a report. The report has been submitted to the supervisor for evaluation.

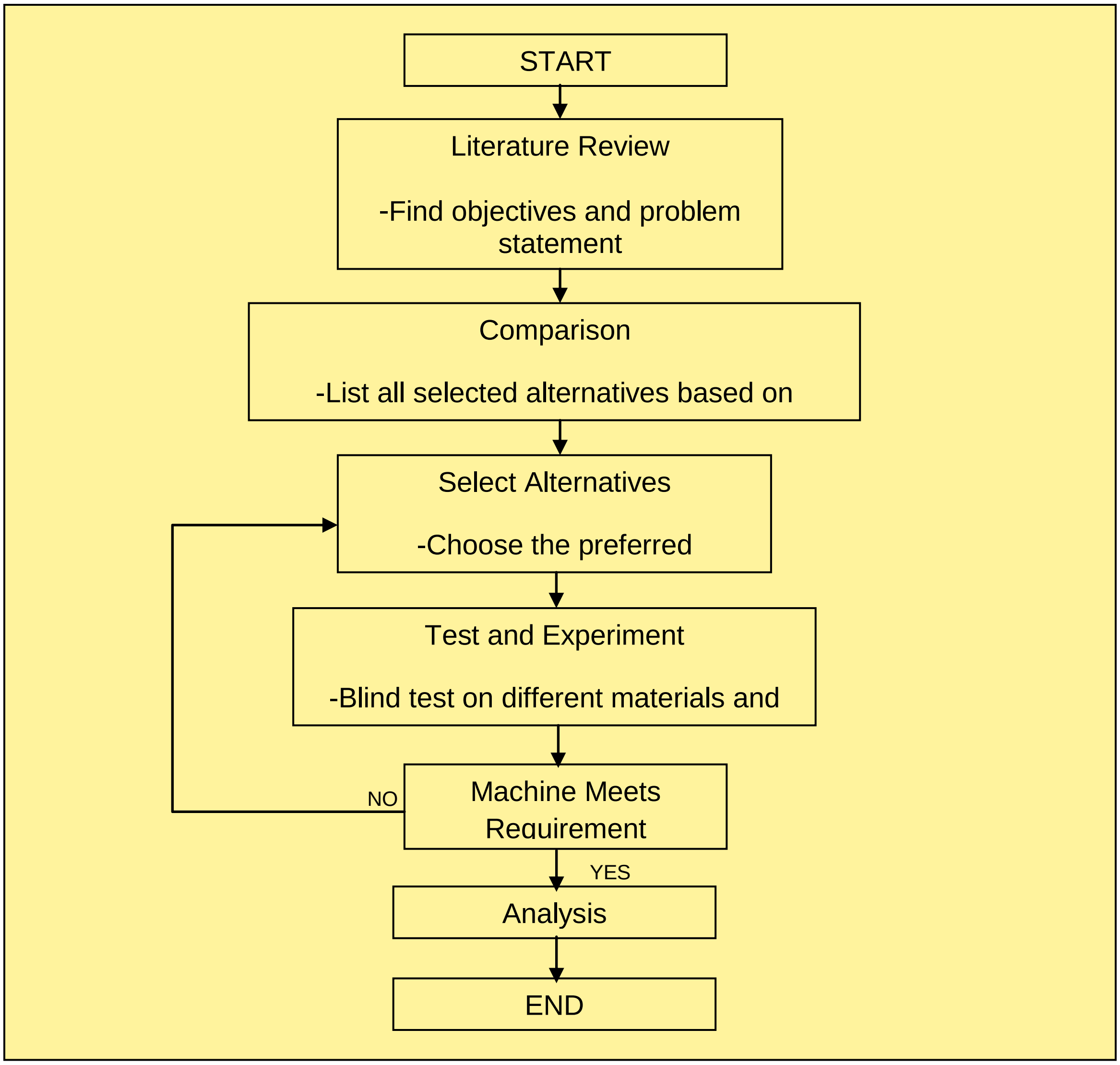


Fig 3.1: Project Flow Chart

3.2 List of Alternative Methods

There are three alternatives have been selected to investigate:

i. Phased Array Technology

ii. Time of Flight Diffraction (ToFD)

iii. Auto UT (AUT)

Table 3.1: Comparison table between all of these alternatives

	RT	UT	AUT	ToFD	PAT
Working Principle	Use radiation energy(x-ray and gamma ray) to examine for internal material discontinuities or material configuration	Measure the thickness of a material, detect possible internal discontinuities e.g. cracks and voids	Advanced UT Technique	Advanced UT technique	Advanced UT technique
Material	All materials	Carbon steel	Claimed to be applicable to all materials	Claimed to be applicable to all materials	Claimed to be applicable to all materials
Defect Location	Surface + Subsurface	Surface + Subsurface	Surface + Subsurface	Subsurface	Surface + Subsurface
Portability	Yes	Yes	No	Yes	Yes
Wall Thickness	Depends on source strength	> 8mm (practically)	>5mm	>2mm	> 0mm
Hardcopy or Softcopy	Hardcopy	Operator judgment	Softcopy & can be printed	Softcopy & can be printed	Softcopy & can be printed
Cost (RM)	350 / day	600 / day	2500 / day	3500 / day	4500 / day

Auto UT consists of a very large component where it can automatically turn the pipe for inspection but it has no portability and also it is difficult to handle especially for site use. For ToFD, a blind test between ToFD and UT (60° probe) has been developed and after the result occurred, there are many errors and undetected cracks occurred for ToFD. Therefore, ToFD has not been selected in this thesis.

Phased Array Technology (PAT) is a very suitable machine to handle in a confined space and time constraint situation. Although the cost is quite expensive, but for the barge rent around 1 million per day, it worth to invest such amount of money to avoid any delay.

3.3 Procedure Identification

There are several experiments conducted in SIRIM, Shah Alam laboratory in order to achieve objectives of the project.

3.3.1 Experiment 1: Search and sizing limitation of Time of Flight Diffraction (ToFD) Methods

Objectives:

i. Investigate the capabilities of TOFD to find and sizing the defects in areas which literature survey says is difficult.

ii. To compare the result with standard reference block.

Equipment used:

Time of Flight Diffraction (ToFD) equipment, couplant and ToFD software

Materials used:

Carbon Steel Plate at the weldment joint

Procedure:

1. Surface preparation
2. Calibration
3. Apply ToFD to the plate
4. Evaluate the data
5. Data is recorded and make a report

3.3.2 Experiment 2 : Search and sizing limitation of Phased Array Methods

Objectives:

i. Investigate the capabilities of Phased Array to find and sizing the defects in areas which literature survey says is difficult.
ii. To compare the result with Radiographic Test (RT) Result.

Equipment used:

Phased Array equipment, couplant and Phased Array software

Materials used:

Carbon Steel Plate at the weldment joint

Procedure:

1. Surface preparation
2. Calibration
3. Apply couplant to the probes and on the plate surface
4. Apply Phased Array to the plate by using sectorial scan range from 35° to 75°
5. Evaluate the data
6. Data is recorded and make a report

3.3.3 Experiment 3: Time comparison between Phased Array and RT

Objectives:

To compare the time taken for Phased Array and Radiographic Test (RT).

Equipment used:

Phased Array equipment and RT equipment

Materials used:

Carbon Steel plate, 12 Curie Iridium-192 source

Procedure for Phased Array:

i. Surface preparation
ii. Calibration
iii. Apply couplant to the probes and on the plate surface
iv. Apply Phased Array to the plate
v. Evaluate the data

Procedure for Radiographic Test:

i. Surface preparation
ii. Set up for RT
iii. Shooting the plate
iv. Waiting for the image to occur
v. Evaluate the data

CHAPTER 4

RESULT & DISCUSSION

4.1 Result & Discussion

4.1.1 Experiment 1: Search and sizing limitation of Time of Flight Diffraction (ToFD) Methods

Table 4.1: Cracks at standard reference block

Test Sample Type	Test Sample Reference	Thickness (mm)	Intended Defect Type	Defect Length (mm)	Defect Height (mm)
Flat Plate	1	40	Root Defect	5	48
	2	40	Porosity	13	30
	3	40	Root Defect	26	51
	4	40	Porosity	24	35
	5	40	Root Defect	40	13

Table 4.2: ToFD result with two experiments at the standard reference block

Test Sample Type	Test Sample Reference	Thickness (mm)	Intended Defect Type	Defect Length (mm)	Defect Height (mm)
Flat Plate	1 (1^{st} exp) (2^{nd} exp)	40	Root Defect	378 171	29 34
	2 (1^{st} exp) (2^{nd} exp)	40	Porosity	0 0	0 0
	3 (1^{st} exp) (2^{nd} exp)	40	Root Defect	25 379	55 54
	4 (1^{st} exp) (2^{nd} exp)	40	Porosity	0 0	0 0
	5 (1^{st} exp) (2^{nd} exp)	40	Root Defect	0 0	0 0

Table 4.3: Comparison table between actual data and ToFD result

Test Sample Reference	Defect Length (mm)			Defect Height (mm)		
	Actual	1^{st} ToFD result	2^{nd} ToFD result	Actual	1^{st} ToFD result	2^{nd} ToFD result
1	5	378	171	48	29	34
2	13	0	0	30	0	0
3	26	25	379	51	55	54
4	24	0	0	35	0	0
5	40	0	0	13	0	0

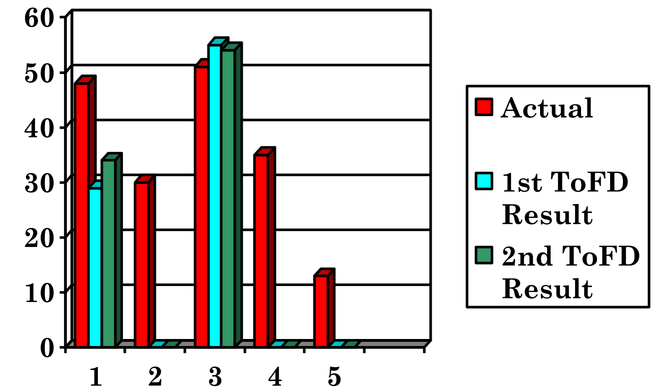


Fig 4.1: ToFD defect length chart

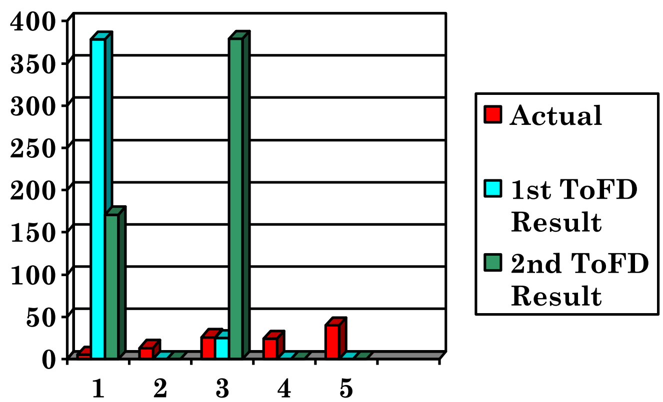


Fig 4.2: ToFD defect height chart

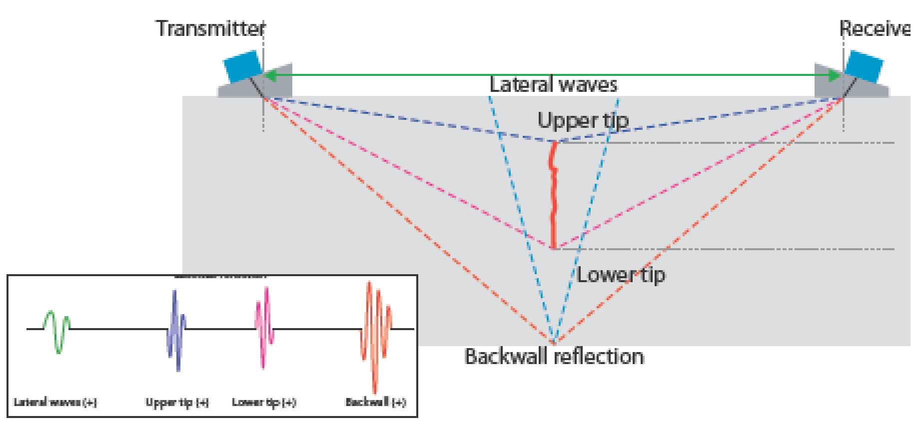


Fig 4.3: ToFD Principle

Conclusion:

From the chart (Fig 4.1 and 4.2), the difference between actual and experimental data so large. Defects number 2, 4 and 5 were not detected. Caution should be exercised when applying TOFD as a stand-alone search technique in situations where the results of this experiment have indicated relatively poor reliability (e.g. detection of “small” root cracks when there may be mismatch across the weld, inspection of welds containing porosity, etc).

4.1.2 Experiment 2 : Search and sizing limitation of Phased Array Methods

Table 4.4: Phased Array Setup (refer appendix II for Phased Array specification)

Beam Delay	11.21 µs
Voltage	40V
Gain	34.90 dB
Wave Type	Shear
Element Quantity	16 elements

Start Angle	35°
Stop Angle	75°
Scan Length	290 mm
Scan Speed	25.0 mm/s
Sound Velocity	25.0 mm/s

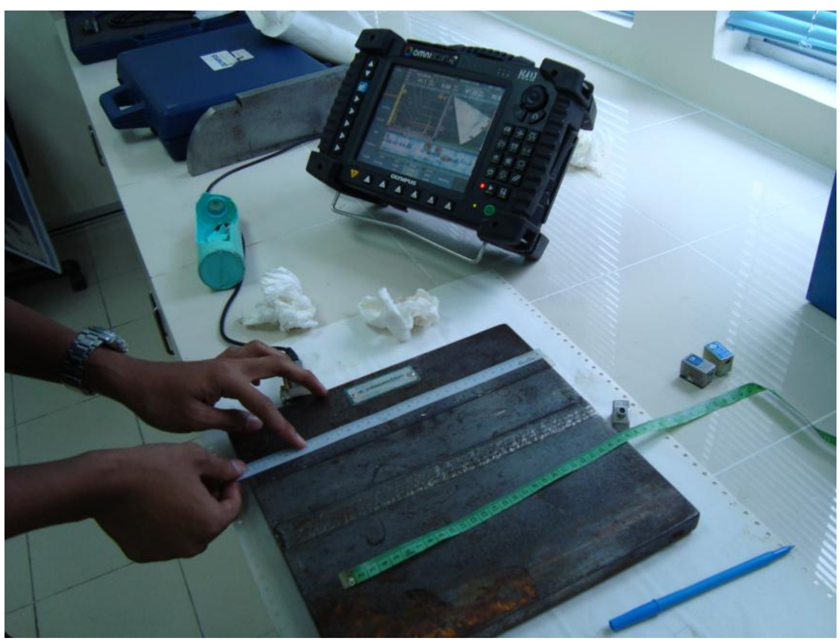


Fig 4.4: Carbon Steel Plate need to be inspected

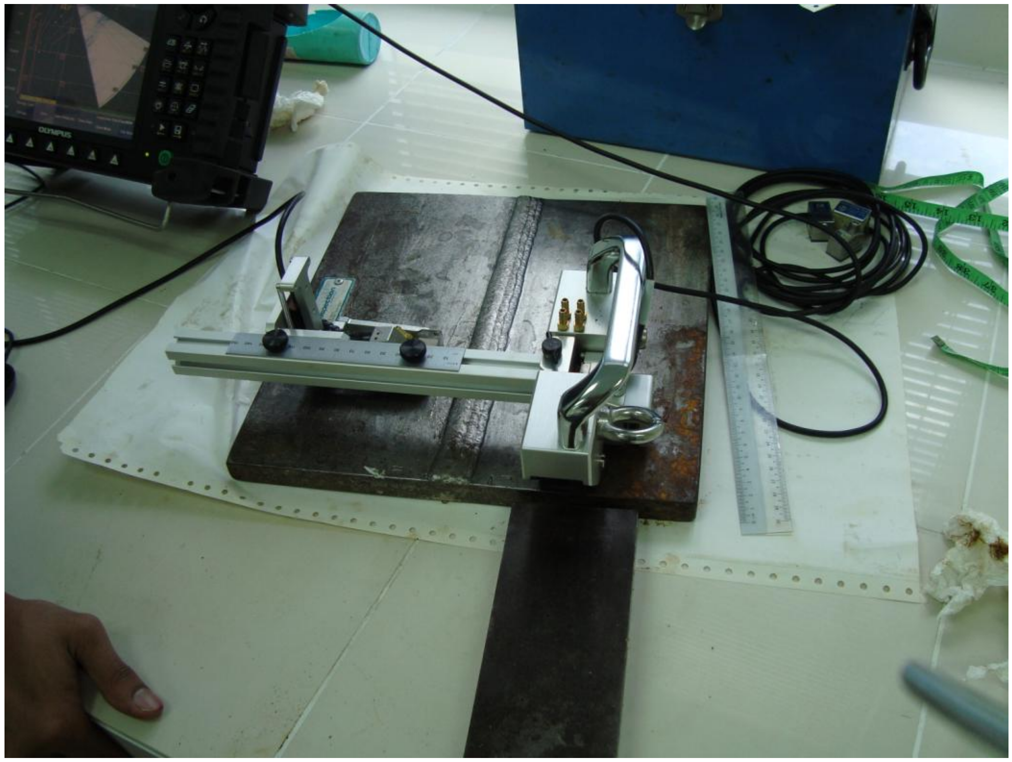
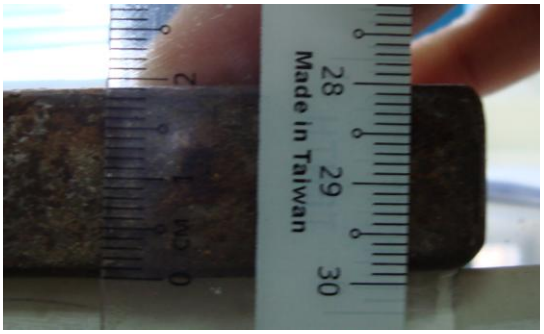


Fig 4.5: Phased Array with the decoder to measure the distance travel for accuracy

Table 4.5: Result by using RT

Test Sample Type	Test Sample Reference	Thickness (mm)	Intended Defect Type	Defect Length (mm)	Defect Depth (mm)
Flat Plate	1	19	Wall Fusion	19	-
	2	19	Lack of Penetrant	15	-
	3	19	Lack of Penetrant	11	-
	4	19	Slag Line	28	-



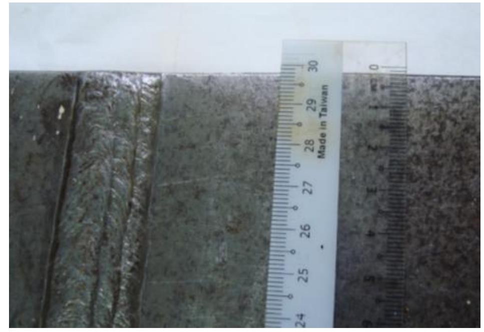


Fig 4.6: Thickness of the plate (19mm) **Fig 4.7: Length of the plate**

(298mm)

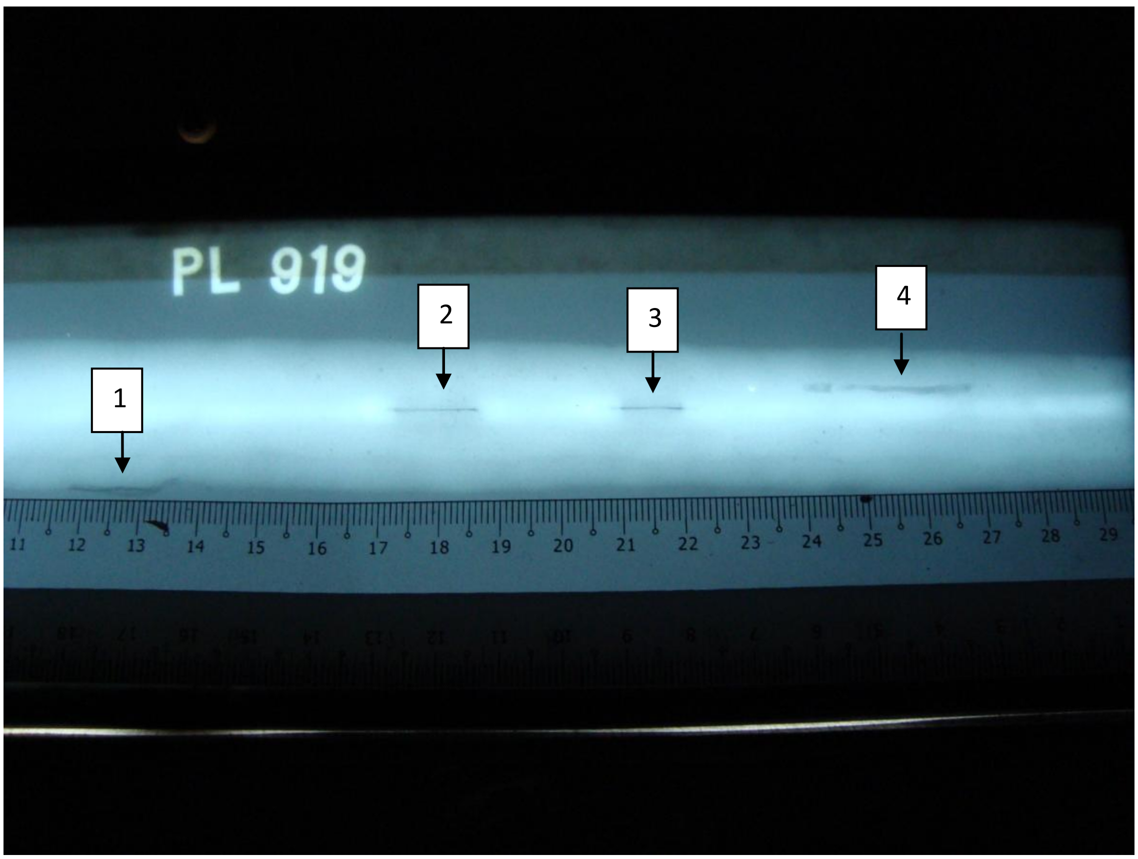


Fig 4.8: It indicates that there are 4 cracks at the weldment

Table 4.6: Result by using Phased Array

Test Sample Type	Test Sample Reference	Thickness (mm)	Intended Defect Type	Defect Length (mm)	Defect Depth (mm)
Flat Plate	1	19	Wall Fusion	19.30	2.09
	2	19	Lack of Penetrant	17.50	18.02
	3	19	Lack of Penetrant	10.20	17.59
	4	19	Slag Line	29.30	4.45

- Test Sample Reference 1:

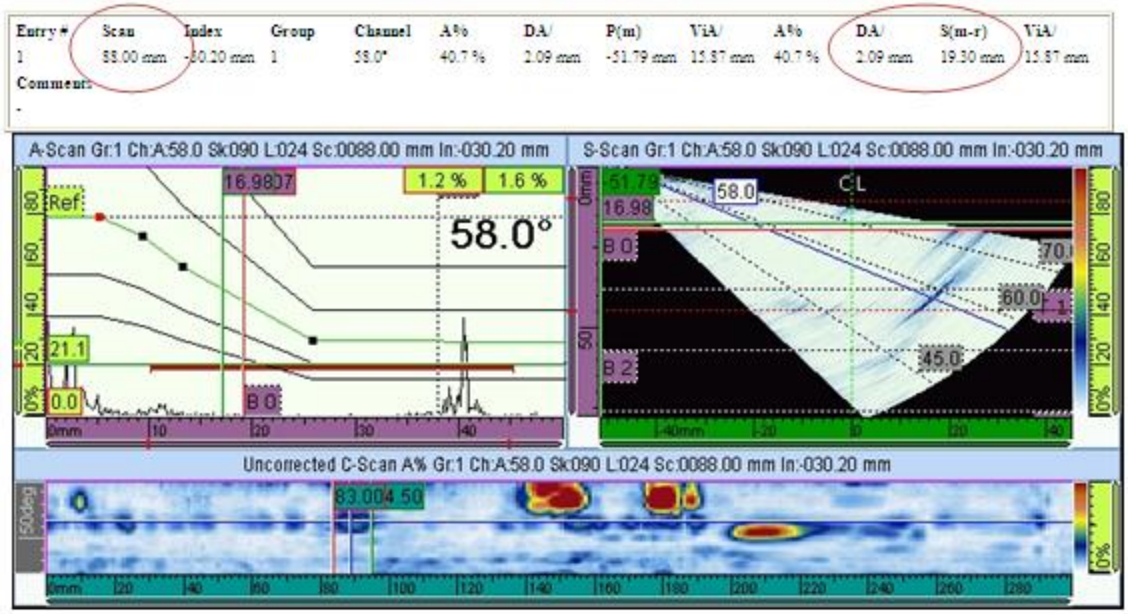


Fig 4.9: Result for the 1st crack. Inside the red circle, DA indicates the depth and S(m-r) indicates the length of the crack. The scan is the location of the crack.

- Test Sample Reference 2:

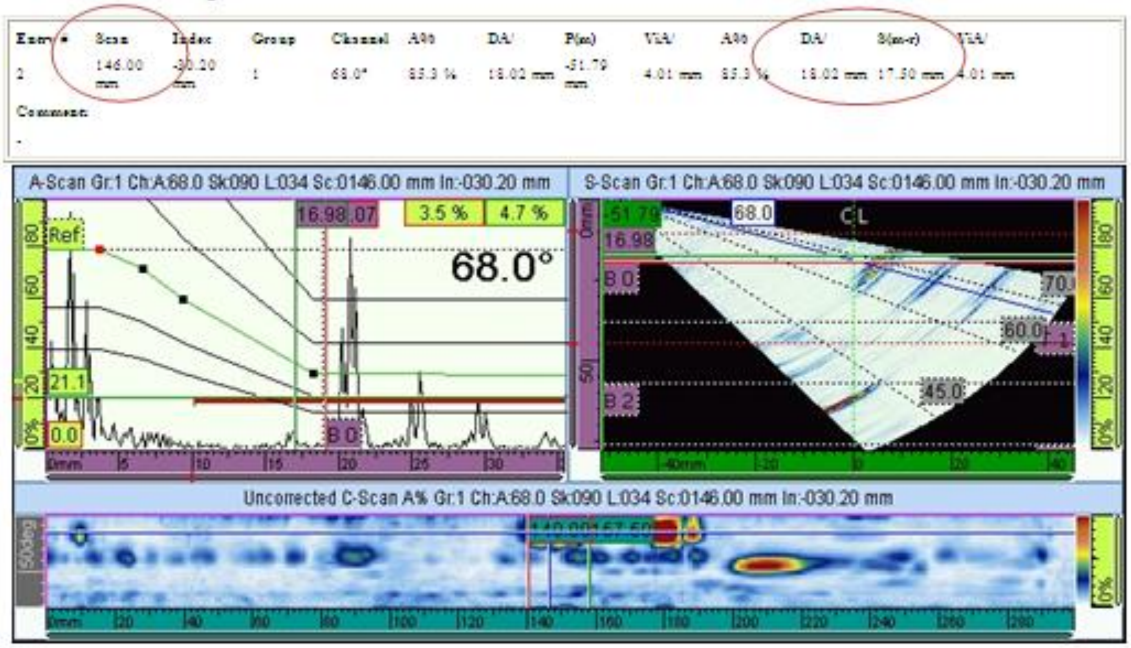


Fig 4.10: Result for the 2nd crack

- Test Sample Reference 3:

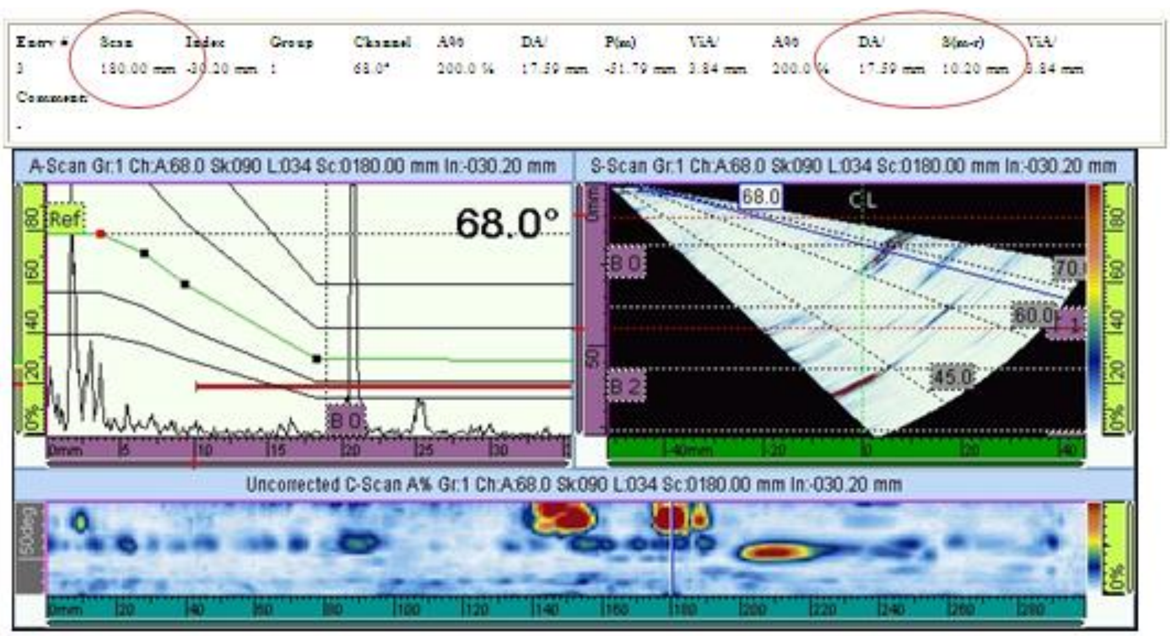


Fig 4.11: Result for the 3rd crack

- Test Sample Reference 4:

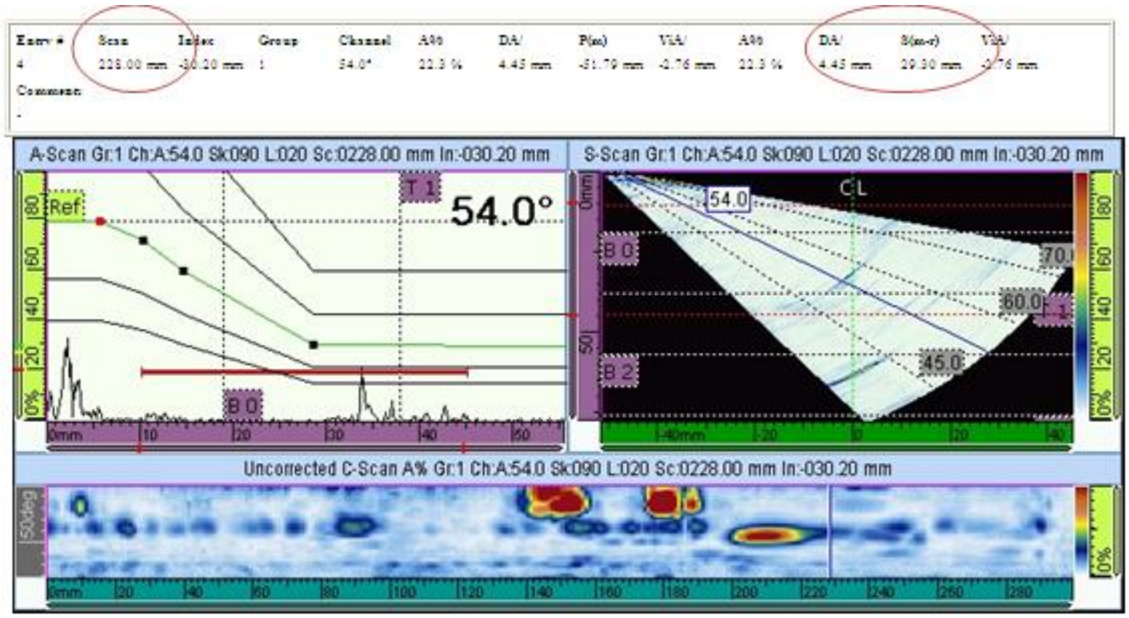


Fig 4.12: Result for the 4th crack

Table 4.7: Phased Array vs. RT Defect Length

Test Sample Reference	Defect Length (mm)	
	RT result	Phased Array result
1	19	19.30
2	15	17.50
3	11	10.20
4	28	29.30

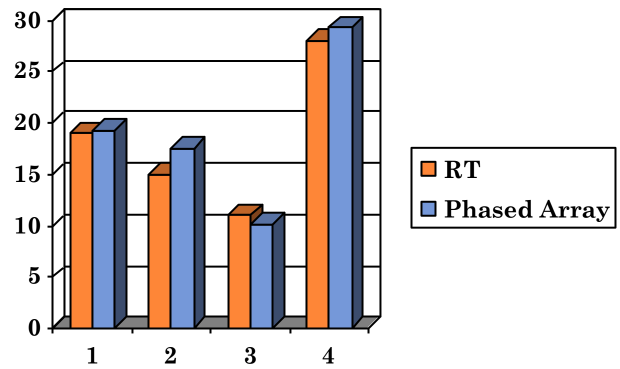


Fig 4.13: RT vs. Phased Array Comparison Chart

Conclusion:

The result from the experiment shows that the difference between RT and Phased Array measurement is not very high. It is almost accurate and the accuracy can be increase if it has been done by the technical expert. Phased Array is more reliable compared to ToFD.

4.1.3 Experiment 3: Time comparison between Phased Array and RT

For RT

Set Up Time = 30 min

Shooting time = 1 min

Film Processing = 30 min

Film Interpretation = 10 min

Total Time = 71 min

For 8 hours of working hours per day, the total linepipe that can be inspected:

Linepipe Inspection Rate = Working hour / Total Time

= 8hr / (71/60)hr

= 6.8 approximate to **7 linepipe**

For Phased Array

Equipment Setup = 10 min

Calibration = 10 min

Inspection = 2 min

Data Interpretation = 10 min

Total Time = 32 min

For 8 hours of working hours per day, the total linepipe that can be inspected:

Linepipe Inspection Rate = Working hour / Total Time

= 8hr / (32/60)hr

= **15 linepipe**

Conclusion:

Phased Array has very fast inspection rate where it took around two times faster than RT. Since this is the laboratory experiment and just for a single plate, the time for an inspection is quite long. But for a repetitive inspection and been done by an expertise, the time can be reduced by performing on a many linepipe with a same materials and dimensions by using the same calibration and setup. Based on technical expert experience, the average for Phased Array inspection rate is around 50 linepipe per day.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Conclusion

This project is to find an alternative of NTD methods that can increase the inspection rate to reduce the gap between production rate and inspection rate for carbon steel linepipe inspection. The safety measure has been taken care of since Phased Array used an ultrasound as a medium for inspection compared to RT where it use radioactivity sources which are hazardous to human. Several experiments have been done in order to prove the reliability and the inspection rate of the linepipe. Phased array is an alternative method that suitable method that can replace RT due to its advanced features and computer controlled technology. It can shows the data in 2 Dimension and further technologies shows that it can be represented in 3 Dimension image. It has a Real Time data where it shows the exact point due to the time or distance of the probe where operators can determine the location, length, thickness and length of the probe. It has several data representation such as B scan, C scan and S scan where it depends on the purpose of inspection. Since Phased Array is no hazardous, many UT groups can be performed to increase the inspection rate to avoid any delay. Although the cost for Phased Array is quite expensive (RM 4500 / day) compared to others technique, but due to its advanced features it reduces the probability of error and it make the task become easier. Compared to the barge cost (RM 1 million per day) it is benefit to invest some money to avoid delay.

5.1.1 Future trend of NDT in industry (S. Vidyasankar, Research Analyst)

i. Digitization - the Wave of the Future

Digital array-based technology simplifies most inspection by improving accessibility and reducing the number of scans required, at the same time providing intuitive real-time images. Hence, the overall transition of the ultrasonic NDT equipment market to digital array-based technology is a significant trend being witnessed and the market acceptance of this technology is bound to grow in the years.

ii. Portable Phased Arrays - having an Edge over High-end Systems

There is tremendous potential for portable phased arrays, which are considered to be most suitable and technically viable for a wide range of applications. Hence, an increased preference of portable phased arrays is being witnessed over high-end systems as they offer higher speed, increased data storage, better imaging, portability, ease of setup, flexibility, and relatively low costs. The phased array ultrasonic market is moving toward portable, battery-operated units with reduced capability. For the portable units, an improved battery technology has significantly increased battery life for these high power demand applications and hence the battery technology continues to evolve.

iii. Cost Cutting gaining significant proportions in difficult market conditions.

Further, cost cutting seems to be the main objective of manufacturing companies, especially in the wake of difficult market conditions. Hence, they are constantly looking for cost-effective equipment. The availability of low priced phased array transducers is critical for inspectors to transition from conventional A-scan inspections to phased array imaging. For example, a conventional ultrasonic test, for the inspection of welds has a user price around RM 350; it will be tough for an inspector to financially justify spending RM 4500 for a phased array transducer - even if it increases inspection coverage and reduces inspection time. Improved cost-effective manufacturing techniques for phased array transducers are increasingly sought and are a significant trend witnessed in the phased array ultrasonic market.

iv. Other notable advancements

Phased array technology is nascent, at least for industrial applications, and hence the market acceptance of such a technology becomes crucial. High resolution imaging is an important requirement for phased array inspections. Over the past five years, improvements in display technology for portable instrumentation, both reduced power consumption and increased display resolution have allowed integration into portable phased array instrumentation".

Improved imaging is increasingly sought for many applications such as aerospace composites and the like, and these are best obtained by phased arrays. There are a number of inspections which were difficult or impossible to perform with manual or conventional ultrasonic or with radiography, which are relatively easily done with phased arrays. Few examples include bolts for cracking, defect sizing, and composites for damage among others. Radiography is becoming more difficult to perform due to increased licensing issues, tighter safety requirements and its inherent limitations in detection and sizing and that is an important trend that has paved the way for phased arrays.

Phased array ultrasonic is expected to revolutionize the NDT industry in the coming years, and it has followed the line of improvement that most other electronic-driven tools have followed. Continuous research has also led to improved electronics, software, and scan-and-display capabilities. These are further expected to improve and change the landscape of the NDT industry. These are some of the trends shaping the future of phased array ultrasonic technology.

5.2 Recommendation

Some recommendations can be considered for further improvement in this project. If extended effort is put in the project and availability of the machine and materials, the better result can be achieved.

5.2.1 Phased Array on a Stainless Steel

For stainless steel material, they require using Cobalt 60 as a radioactive source which is more hazardous and contains higher energy level even though they have the same Curie with Iridium 192. It means it requires a larger safety distance and not suitable at fabrication yard. UT cannot be performed on stainless steel due to attenuation which means the large grain structure absorb or reflect the waves until it lose its energy. In theoretical Phased Array can be using on stainless steel since it can use longitudinal wave which has higher energy. The angle of longitudinal wave can be adjusted to do the inspection.

5.2.2 Inspect on all types of cracks

For further study, Phased Array must have to detect all types of cracks such as toe crack, lack of fusion, porosity, side inclusion and etc. This is important since in linepipe weldment, this cracks will occurred so Phased Array must have the reliability to detect all type of cracks. A reference block which contains all type of cracks must been done by the manufacturer and a comparison test between actual data and Phased Array result must been done. It is to detect the limitation of Phased Array or improved the technique of inspection to increase the probability of detection.

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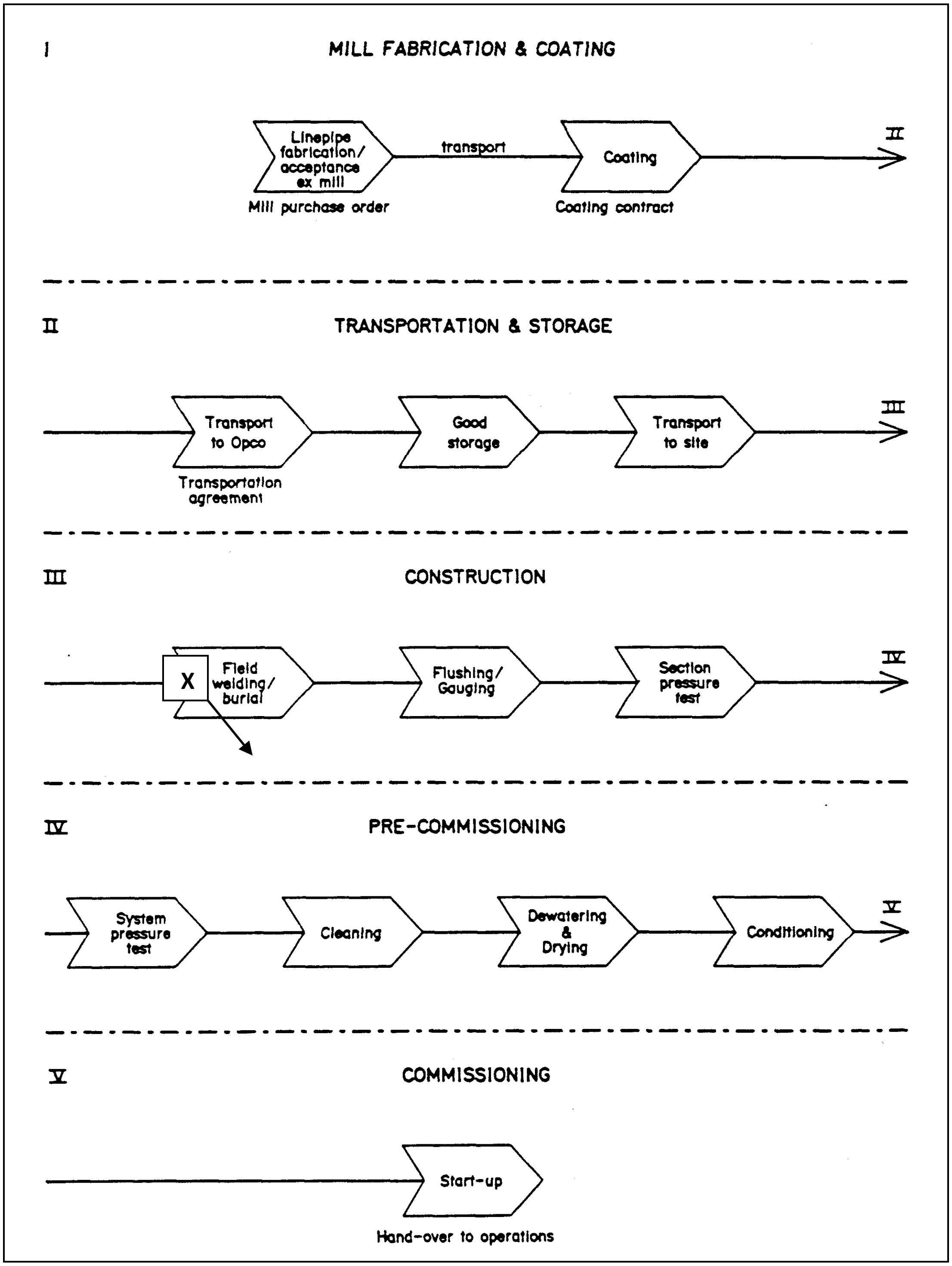
APPENDIX 1



The stages of construction and commissioning of a pipeline prior to operation.

Where “X” is the area covered for linepipe inspection (ref: PTS 20.107)

APPENDIX II

OmniScan MX Specifications

Overall dimensions	321 mm x 209 mm x 125 mm (12.6 in. x 8.2 in. x 5 in.)
Weight	4.6 kg (10.1 lb) (including module and one battery)
Data storage	
Storage devices	CompactFlash® card, most standard USB storage device, or through fast Ethernet™ Internal 32 MB DiskOnChip®
Data file size	160 MB
I/O ports	
USB ports	3
Speaker out	Yes
Microphone input	Yes
Video output	Video out (SVGA)
Video input	Video input (NTSC/PAL)
Ethernet™	10/100 Mb/s
I/O lines	
Encoder	2-axis encoder line (quadrature, up, down, or clock/direction)
Digital input	4 digital inputs TTL, 5 V
Digital output	4 digital outputs TTL, 5 V, 10 mA
Acquisition on/off switch	Remote acquisition enable TTL, 5 V
Power output line	5 V, 500 mA power output line (short-circuit-protected)
Alarms	3 TTL, 5 V, 10 mA
Analog output	2 analog outputs (12 bits) ±5 V in 10 kΩ
Pace input	5 V TTL pace input
Display	
Display size	8.4 in. (diagonal)
Resolution	800 x 600 pixels
Number of colors	16 million
Type	TFT LCD
Power supply	
Battery type	Smart Li-ion battery
Number of batteries	1 or 2 (battery chamber accommodates two hot-swappable batteries)
Battery life	Minimum 6 hours with two batteries; minimum of 3 hours per battery in normal operation conditions
DC-in voltage	15 V – 18 V (min. 50 W)
Environmental specifications	
Operating temperature	0°C to 40°C (35°C with 32:128 PA)
Storage temperature	–20°C to 70°C
Relative humidity	0–95% non condensing. No air intake, splashproof design.

Phased Array Module Specifications

(Applies to OMNI-M-PA16128)

Overall dimensions	244 mm x 182 mm x 57 mm (9.6 in. x 7.1 in. x 2.1 in.)
Weight	1.2 kg (2.6 lb)
Connectors	1 OmniScan connector for phased-array probes 2 BNC connectors (1 pulser/receiver, 1 receiver for conventional UT) (BNC not available on models 32:32 and 32:128)
Number of focal laws	256
Probe recognition	Automatic probe recognition and setup
Pulser/Receiver	
Aperture	16 elements*
Number of elements	128 elements
Pulser	
Voltage	80 V per element
Pulse width	Adjustable from 30 ns to 500 ns, resolution of 2.5 ns
Fall time	Less than 10 ns
Pulse shape	Negative square wave
Output impedance	Less than 25 Ω
Receiver	
Gain	0–74 dB maximum input signal 1.32 V p-p
Input impedance	75 Ω
System bandwidth	0.75–18 MHz (–3 dB)
Beam forming	
Scan type	Azimuthal and linear
Scan quantity	Up to 8
Active elements	16*
Elements	128
Delay range transmission	0–10 µs in 2.5-ns increments
Delay range reception	0–10 µs in 2.5-ns increments
Data acquisition	
Digitizing frequency	100 MHz (10 bits)
Maximum pulsing rate	Up to 10 kHz (C-scan)
Acquisition depth	29 meters in steel (L-wave), 10 ms with compression. 0.24 meter in steel (L-wave), 81.9 µs without compression
Data processing	
Number of data points	Up to 8000
Real-time averaging	2, 4, 8, 16
Rectifier	RF, full wave, halfwave +, halfwave –
Filtering	Low-pass (adjusted to probe frequency), digital filtering (bandwidth, frequency range)
Video filtering	Smoothing (adjusted to probe frequency range)
Data storage	
A-scan recording (TOFD)	6000 A-scans per second (512-point 8-bit A-scan)
C-scan type data recording	I, A, B, up to 10 kHz (amplitude or TOF)
Maximum file size	Limited by memory size
Data visualization	
A-scan refresh rate	Real-time: 60 Hz
Volume-corrected S-scan	Up to 40 Hz
Data synchronization	
On internal clock	1 Hz – 10 kHz
On encoder	On 1 or 2 axes
Programmable time-corrected gain (TCG)	
Number of points	16 (1 TCG curve per channel for focal laws)
Alarms	
Number of alarms	3
Conditions	Any logical combination of gates
Analog outputs	2

* Models 16:16, 16:16M, 16:64M, 32:32 and 32:128 also available