University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization:

- Mechanical and Structural Engineering and Material science
- Offshore Field Development Technology

Spring semester, 2015

Open / ~~Restricted access~~

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Thesis title:

"Evaluating Ultrasonic Tomography (UT) Methods used for the Inspection of Offshore Pipelines"

Credits : 30

Key words:

- Ultrasonic Transducers
- Corrosion &Weld Inspection
- Gas Hold-up & Hydrate Inspection
- Flow Measurements

Pages: 71
Stavanger: 15 June 2015

University of Stavanger

Abstract

In the oil and gas industry, safe and trustable operations of a pipeline system need guidelines for operations and maintenance. These guidelines should be used to optimize the operations by improving product output and uniformity, lowering the input process requirements, decreasing the energy consumption and environmental impact and lowering the number of plant personnel. Real-time process monitoring also plays an essential role in providing efficient operations by providing quantitative data as accurately as possible and by consideration of hydrodynamic parameters like flow regime and flow rate. It will be suggested that imaging and measurements of the pipeline content in order to inspect can be achieved by an *ultrasonic tomography system*.

One of the challenges that we might be faced with in these regards is the barrier at the seafloor, which makes some disturbance for sensors in order to monitor the pipeline. It could also be difficult to mount the ultrasonic tomography array appropriately. The occurrence of a complex sound field, that causes overlapping or multiple reflected pulses, is another impediment that leads to further errors. Furthermore, there is a significant problem in using ultrasonic tomography as we use metal pipes, because the ultrasonic energy is attenuated dramatically in metal, and there are the large effects of Lamb waves. If we, however, achieve an appropriate technique of the ultrasonic tomography system for flow sensing, we will be able to monitor flow disturbance inside the pipe.

Here, we suggest that a non-invasive ultrasonic tomography system is feasible; that is, we suggest that the offshore industry will solve the challenges of monitoring. This will involve cooperation between two teams composed of;

1. Physicists, Chemists and Subsea Specialists (to create an efficient sensor system and to mount and implement the sensors),
2. Computer Programmers (to provide cross-sectional images of the objects inside the pipelines, identifying and profiling debris determining wall metal loss and to provide a snapshot of the flow regime).

The objective of this thesis is to describe the technique of non-invasive ultrasonic transducers, and investigate how ultrasonic waves propagate in the pipeline flow field. For this purpose, there will be emphasis on the ultrasonic tomography techniques; a description of ultrasonic waves and how they propagate.

Subsequently the use of the non-invasive ultrasonic tomography method in offshore pipelines will be discussed. After obtaining the relationship between the ultrasonic waves’ propagation and their frequencies, a perception of non-invasive ultrasonic tomography in subsea pipelines and the development of an installation application will be considered.

Acknowledgments

The only name that appears on the cover page of this thesis is my name, however great numbers of people have contributed to its production. I owe my gratitude to all of those who have made the creation of this dissertation possible and because of them my graduation experience has been the one that I will appreciate forever.

First and foremost, I would like to express my boundless gratitude to my Professor and internal Supervisor, Ove Tobias Gudmestad, who spent so much time and put a lot of effort on the guidance and supervision of my thesis. Professor Ove Tobias Gudmestad supported me by providing valuable and helpful suggestions from finding an appropriate topic in the beginning to the process of writing the thesis. I have been amazingly fortunate to have an advisor who gave me the opportunity to explore on my own, while delivering me the guidance required for reaching to high research standards.

Moreover, I would like to thank my external Supervisor Joachim Sannes, at Halliburton, for making it possible to gain experience in the industry by cooperating on this thesis. I am particularly grateful for the valuable advice and support given by the Halliburton team, composed of the following specialists; Laurence James Abney, Neil Mackay.

Finally, none of this would have been possible without the love and patience my parents had to me. This thesis is dedicated to my parents who have been endless sources of love, concern, support and strength through all these years and have provided me with a carefree environment to be able to concentrate on my studies. I would like to express my warm appreciation to them. I consider myself to be lucky to have them as my parents.

Stavanger, 15.Jun. 2015

Sara Jalali

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1. 1 Introduction

There are thousands of kilometers of pipelines around the globe both offshore and onshore that are being used extensively. Operating these pipelines and their dependent facilities requires specific proficiency along with experience.

Pipeline operators and those who are responsible for pipelines are interested in finding the most cost effective and optimal techniques to improve the operations in the competitive oil and gas industry.

Inspection and maintenance play an effective role in this industry. There are three categories of hazardous accidents that can threaten the integrity of a pipeline as a transportation system. The first is third party damage, which includes accidents leading to unwanted features, such as; dents, buckles and wrinkles that leads to problems into the pipeline. Damage caused by criminal gangs who will steal oil are also included in this category (Agbakwuru, 2013).

The second consists of incidents that have the potential to threaten the environment such as corrosion, cracking, erosion, leakage and chemical attacks.

The last is construction or material destruction, such as failures in weld pinholes, girth welds, and hard spot creation. For example, a small leak suddenly occurs in an important segment of the pipeline, which needs to be detected. Leak detection and leak prevention is very important in a pipeline system to avoid hazards induced by leakage, such as explosion, loss of throughput and environmental impacts. Welding inspection systems is another issue, which has significant impacts on the probably of hazardous pipelines (Ozanne, 2011).

Today very much research and development efforts (R&D) are involved to improve automatic welding systems in the pipeline industry. Automatic welding machines help improve the pipeline production and to raise the deposition rate of welding. Also, global experience suggests that automatic welding has been used much for large diameter gas pipelines such as 36-in size and larger. In these cases, very appropriate methods are required to check the girth weld integrity (Bubar, 2011b). Internal and external inspections are two main pipeline inspection categories. Intelligent pigging as an internal inspection method has been used for approximately 80 years in the pipeline industry. Although this technique has performed successfully in many cases, there are some problems to implement it for older pipeline systems. These aging systems have not been designed for long-term maintenance; therefore their design is not appropriate for a pigging system.

Most of them operate without many valves, including sufficient check port valves and no pig launcher/receiver system. Some pipelines were installed that with small bending radiuses that cause the pig

To stall due to bypass. Moreover, some of these older pipelines have been developed and connected to tnew pipelines, accordingly their diameters change in some sections. Also, some connections were not protected at branches by using bars in pipe tee connections to prevent the pigs to block the flow (Bubar, 2011a). There is also a probable risk for pigs to be trapped inside the pipeline especially in valves and U-bends.

The internal inspection category for offshore flow line inspection contains various techniques of Non-Destructive Testing (NDT). NDT methods based on The American Society of Non-Destructive testing procedure (ASNDT) can be introduced, such as: The process consisting of inspection, test or evaluation of a material for the purpose of controlling the integrity of assemblies and the components' characteristics without any physical change that could destroy the serviceability of part or whole of the system (Ref: ASNDT)

ASNDT includes the following types of NDT methods: Acoustic Emission Testing (AE), Electromagnetic Testing (ET), Laser Testing Methods (LM), Leak Testing (LT), Magnetic Flux Leakage (MFL), Liquid Penetrant Testing (PT), Magnetic Particle Testing (MT), Neutron Radiographic Testing (NR), Radiographic Testing (RT), Thermal/Infrared Testing (IR), Ultrasonic Testing (UT), Vibration Analysis (VA) and Visual Testing (VT) (Ref: ASNDT).

NDT as a range of high valuable analysis techniques applicable in research, science and industry does not permanently alter the equipment item being inspected. In addition, it has a potential to save time in product evaluation, troubleshooting and research.

Nondestructive testing (NDT) has been developed for the pipeline inspection field. In this Master's Thesis we are going to expand on the ultrasonic tomography system, which is a more accurate and beneficial method to qualify pipe weld integrity. The ultrasonic tomography system also provides advantageous information about flow components such as flow regime and rate via cross sectional images from the pipeline. Furthermore, the ultrasonic tomography system is capable to give measured real time data regarding the content without any discontinuity during the industrial process. This system has the ability of on-line investigation and enables us to gain extensive information, using non-invasive and non-intrusive controlling systems that will be discussed comprehensively later. Ultrasonic Testing as a technology, that gives more properties of an object that are not achievable by other methods and; as such has greater applicablility in the pipeline offshore industry (R. A. Rahim, M. H. F. Rahiman, K. S. Chan, & S. W. Nawawi, 2007).

For instance, Ultrasonic Testing in comparison to Radiographic Testing (X-ray) is more secure for health and environment because there is no radiation in this method. Moreover, it has potential to evaluate automatic welds very quickly, almost 5 times faster than the X-ray method. The ultrasonic method consists of sending ultrasound waves to the pipeline and provides a 3D indication on a computer. By this method, there is the possibility to investigate, for example, a weld with a developed defect and obtain information such as the defect location, size and other details. By this way, the inspector can address a specific defect directly to save-time and cost (Bubar, 2011b).

1.1. Objectives

The intention of this thesis is to provide authoritative and extensive research about pipeline inspection by ultrasonic tomography system. To satisfy this purpose the following objectives have been projected:

- General objective : Evaluating the conventional ultrasonic tomography systems which are applied in pipeline operations
- Specific objective : Study the efficiency of the existing ultrasonic tomography system particularly in the fields of corrosion and weld inspection, flow metering, gas hold-up, solid particles situation and hydrate localization

1.2. Pipelines

The seven basic scopes of qualification in mechanical engineering arrangement include materials, design, construction, inspection, testing, maintenance and operations (Antaki, 2003). As below, it has been attempted to offer a concise explanation for each of them.

The material in a pipeline system is categorized in two large groups of metallic and non-metallic. Ferrous materials as iron based materials and non-ferrous materials such as copper, nickel or aluminum compose the metallic pipes. Non-metallic material classified as non-plastics, plastics and thermoplastics (Antaki, 2003). In order to install a new line or modify an existing line the required material for design and construction of pipeline should be defined. For this purpose the product, daily carried volume, operational pressure, location of pipe installation and construction should be taken into account (Menon, 1978). Pipeline steel which is usually deployed for pipelines at high pressure at more than 100 psig (Menon, 1978) must have a balance of property competence such as high strength, ductility, toughness and weld ability (Palmer & King, 2004).

Suitability of the design methods depends on several items such as system, the number of constant variables, designer, affordability and availability of equipment. The most challenging issue concerning the pipeline design is to estimate the volume of oil and gas to be transported. (Kennedy, 1993). For structural design of offshore pipelines, see DNV-OS-F101 (DNV, 2014)

Pipeline construction methods vary, based on geographical properties of the area, environment situation, terrain, limitations and standards established by government or agency regularity. Offshore pipeline construction is governed more by installation changes rather than operating challenges. Additionally, the environmental forces play a considerable role in offshore construction design. All offshore construction methods need large complicated marine vessels applying; conventional lay barge method, reel-barge method, vertical lay method and tow method (Kennedy, 1993).

Pipeline inspection programs are implemented for three following purposes (Kennedy, 1993):

- Prevention from mechanical damage
- Keeping pipeline continuous
- Keeping pipeline safety during the operations.

The substantial consideration about the monitoring programs are their affordability and suitability (Kennedy, 1993). Maintenance ensures that the physical asset supports the systems to fulfill their functions such as: instrumentation, controls, heat tracing, power and air supply to valve operators (Antaki, 2003).

Pipeline hydrostatic testing is normally carried out in the space between two closed valves to determine the leakage rate. Pipeline testing for both gas transmitting pipelines and liquid pipelines is almost the same, except that after testing and removal of the water, the gas pipeline should be cleaned and dried underneath 0°F dew point (Menon, 1978).

Operations and production surround all those mentioned areas so that beneficial and authoritative operations are the final purpose of all these activities.

1.3. Ultrasound History

Although ultrasonic due to an industrial demand, developed very quickly during the 19th and 20th centuries, the knowledge about sound waves is rooted to older times. Chrysippus was a Greek philosopher who considered the sound from water waves for the first time in 240 B.C. However, Galileo Galilei who is well known as the “Father of Acoustics” and Marin Mersenne developed the first law for controlling sounds at the end of 16th and beginning of 17th Centuries (Peter & Bernard, 2002).

In 1686, Sir Isaac Newton was the next person who expanded mathematically the first theory of sound. This theory introduced sound as a series of pressure pulses, which travels within the particles. His theory presented some characteristics of waves, such as diffraction, as well. Euler, Lagrange and D’ Alembert created the wave equation by further developing Newton’s theory. This given wave equation presents the sound waves by a mathematical expression (Peter & Bernard, 2002).

Lord Rayleigh was one of the pioneer scientists in ultrasonic study. He discovered the Rayleigh surface waves at the end of 19th century. He had cooperation with Lamb who discovered the waves in plates, which are called Lamb waves (Peter & Bernard, 2002).

This history indicates that most of the solutions for the wave propagation problems were found in the 19th century. Thereafter computers enabled us to solve complicated problems related to multilayered objects or to analyze different reflections from defects. It is interesting to know that first, the ultrasonic waves were discovered and then scientists were able to generate and understand them. Then the ultrasonic method was applied as a kind of NDT method to inspect defects that are more critical. In 1880, the brothers of Curie invented the direct piezoelectric effect. This effect consists of the usage of the crystals for transforming the ultrasonic energy to electrical energy. Just one year later, Lippmann detected the indirect piezoelectric effect what was the inverse of the direct piezoelectric effect. In the other words, the indirect piezoelectric effect means to convert the electrical energy to ultrasonic energy in the same crystal (Peter & Bernard, 2002).

After the sinking of the Titanic, iceberg detection at sea in 1912 was the preliminary attempt for practical use of the mentioned ultrasonic discoveries. This experiment was also the background for some other underwater feasible works, such as submarine detectiories during the First World War. Around 1930, two big achievements in ultrasonic applications were obtained. First, Sokolov tested the materials by using ultrasound. Secondly, by using the pitch-catch method, Mulhauser invented an ultrasonic device to detect flaws. The pitch-catch method consisted of a separated transmitter transducer and a receiver transducer (Peter & Bernard, 2002).

A decade later, the Iron and Steel Institute developed the ultrasonic method for purpose of checking strength and performance of their products, which had also two transducers. In this period, the continuous-wave method was employed typically for ultrasonic testing. This method was difficult to interpret because they had acutely low signal to noise proportions. At the beginning of 1940's the concept of pulsed ultrasound was published by Firestone and Simmons. This innovation was a revolution in ultrasonic testing compared to the continuous-wave method (Peter & Bernard, 2002). Continuous signal and pulsed signal are two common types of ultrasonic signals. Continuous signal provides a continuous effect on the object while a pulsed signal gives the opportunity to determine the interval of the transmission and reception signal (R. Abdul Rahim et al., 2007).

Firestone also introduced the Pulse-echo system in which there were single transducers that doubled both transmitter and receiver. This method was named “echo-reflection” used supersonic reflect scope. Fundamental of the echo-reflection offered the basics of today modern ultrasonic testing techniques (Peter & Bernard, 2002).

The Immersion system and various imaging methods constitute the modern ultrasonic technologies. Tomographic reconstructions and the acoustic microscopes are the examples for imaging techniques. In addition, the tone-burst is another system, which determines the signal to hit the transducer and provides the possibility to govern the testing excellently (Peter & Bernard, 2002).

2. Ultrasonic Waves

2.1. Introduction

The aim of this section is to give the comprehensive definition of ultrasonic waves as one of the basic component of the ultrasonic method. Within this chapter, types of ultrasonic waves and their propagation will be discussed. To perceive how waves reflect off at different materials interfaces, notions of the “Wave Reflection” and “Refraction” will be defined. Furthermore, the meaning of the wave attenuation, wave impedance, wave characteristics and pattern of motion will be explained.

What is the ultrasound wave? The answer can be understood from the name “ultrasonic” where “ultra” means high and “sonic” means sound. By this explanation, ultrasonic wave is a kind of wave that its frequency is in excess of a human’s highest hearing limit. This is the reason that people who are involved in ultrasonic testing are not able to hear the frequency of the sound wave vibration. The sound frequency range, that humans can hear is between 20Hz and 20,000 vibrations per second (Hz). However, the ultrasound wave frequency is normally higher than 20,000 Hz and can reach GHz (Peter & Bernard, 2002).

It will be interesting to study the material, which sound waves propagate through. From the hearing process it can be understood that sound waves not only propagate through the air, they can also propagate easily through liquids and solids. They can even propagate through solids and liquids with higher velocity and lower loss of energy than through the air. However, the sound waves are not able to propagate through a vacuum. This property is completely opposite to the electromagnetic waves (lights) that propagate through vacuum with higher quality than through a solid (Peter & Bernard, 2002).

The ultrasonic wave propagation through liquids and solids has a dominant role in ultrasonic tomography system. Ultrasonic specifications such as transmission time (velocity) and energy attenuation help us to determine the material’s property such as form, composition, density, velocity and so on. Furthermore, the ultrasonic waves are used to characterize the probable flaws and defects. The reflection of these flaws against the ultrasonic waves, produce a scattering like an echo. By detecting this echo, we can understand the flaws shape, location and the other properties.

2.2. Wave Propagation

When a wave distributes through a substance from its equilibrium state, wave propagation happens. Therefore, the material particles oscillate in their place without traveling through the material’s body. In the other words, the energy is what propagates, that is the point that should not be confused about the waves ‘propagation (Peter & Bernard, 2002).

To understand how a wave propagates, we should first notice the wave shape. In reality a wave is usually curved, when it propagates from its origin. The wave does not normally distribute in two dimensions as a straight line or in three dimensions as a planar. However, to simplify the work, it is usually assumed that the waves distribute in a straight line or as planar in shorter distances. Here we assume that the shape of ultrasonic wave is as plane wave (Peter & Bernard, 2002).

The ultrasonic waves propagate as two different types of planar waves:

1. Transverse Mode: The body particles vibrate perpendicular to the direction of the wave travelling. The vibration of the wave transverse particles is along with the shear stress. Shear stress and definitely shear waves cannot be supported by those fluids, which have low viscosity such as air or water.
2. Longitudinal Mode: The body particles oscillate along the direction of the wave propagation. The stress of the periodic compression and tension off the solid particles is parallel to the wave propagation.

Shear waves

Shear waves are not as strong as longitudinal waves. They travel through the body of an object as a transverse wave, so the direction of their transmitting is perpendicular to wave propagation direction.

Longitudinal waves

Longitudinal waves travel in the same direction as the particles. Longitudinal and Shear waves are the most common in Ultrasonic Testing. There are some types of forces in longitudinal waves that make them compress or expand. Hence pressure or compressional waves, are the other names for longitudinal waves. As longitudinal waves propagate through the material, the density of the particles starts to rise and fall irregularly. Therefore, these waves are also called density waves (Peter & Bernard, 2002).

2.2.1. Guided waves

In this section, we will consider waves while they are bound to a surface and in the finite medium (two boundaries). In the finite medium, the waves are with in the medium and there is a possibility to resonate.

2.2.2. Acoustic waves

A surface acoustic, wave (SAW) is a unique composite of longitudinal and shears waves. SAWs transmit through the surface of material and as long as their wavelength allows them, are able to penetrate into the object (R. Abdul Rahim et al., 2007).

The amplitude of a SAW decreases exponentially as it propagates within the material. The nature of the materials that are in interaction make different kinds of elliptical or complex vibrations of the particles at a surface. Rayleigh, Love, Scholte, Stoneley, Bounded and Longitudinal Creeping are the most current examples for SAW (Peter & Bernard, 2002).

2.2.3. Rayleigh Waves

A Rayleigh wave is a SAW that propagates at the interface between air and a substrate. At the beginning of propagation, the Rayleigh wave is the transverse wave. However, during transit it converts to a wave, which has both properties of transvers and longitudinal waves. Since Rayleigh waves can adjust themselves to curved surfaces easily. Therefore, they are the best solution for finding the defects at the surface of curved objects. Propagation of this wave around corners and surfaces can face some reflections and likewise some changes in velocity.

As the ratio of the curvature radius to the wavelength is a large value, the Rayleigh wave velocity is the same as the velocity on flat plate. By reducing the ratio, the velocity increases almost equal to the velocity of the transverse wave (Peter & Bernard, 2002).

By using the Rayleigh equation, we can obtain the Rayleigh wave's velocity:

$$\frac{v_r}{v_t} \cong \frac{0.87+1.12v}{1+v} \qquad (1)$$

As the Poisson's ratio, v , changes from zero to 0.5, the velocity of the Rayleigh wave v_r changes from 0.87 to 0.96 times the transverse velocityv_t.

2.2.4. Love Waves

Love waves travel through the surfaces, which are not homogenous such as earth-layered constructions. Love waves importance is in seismology studies. These studies help us to understand the large displacement components of the transverse waves (horizontal plane) as the main vibration of an earthquake. These displacements are not counted into the Rayleigh waves specifications because their displacements are only in vertical plane. Love waves are built up from the horizontal shear waves, which are trapped in the surface layers of the earth. Then they will be distributed by multiple reflections into those earth's layers.

2.2.5. Scholte Waves

A Scholte wave travels along a boundary of water and solid. Its velocity is approximately equal to the Rayleigh wave velocity but has higher attenuation in comparison to the Rayleigh waves. For this reason Scholte waves are also called leaky surface waves, which lose their energy through the surface. This property is employed where there is thin water with a homogenous thickness on a material. In this situation, the energy of Scholte wave leaks away into the water and is reflected back to the surface. By this way, the next surface wave will be created at the interface.

2.2.6. Stoneley Waves

Stoneley waves propagate along a boundary of solid-solid interface. For some particular compounds of material, the wave can be restricted along the boundary between two solid media. Currently numerical computation estimates the velocity of the wave propagation and field distributions. Field distribution consists of two partial waves declining away through the surface in each media. We use some simple guidelines about the Stoneley wave's propagation (Peter & Bernard, 2002).

For example, the velocity of these waves should remain among Rayleigh waves and shear waves in the medium with more density. In other words, the solutions depend on the ratio of the longitudinal to shear velocity in denser medium.

2.2.7. Bounded Waves

The ultrasonic waves create the bounded waves in those substances, which have finite borders of the medium. Bounded waves are typically referred as plate waves for multilayered structures and as lamb waves for the single layer. When a longitudinal wave hits a surface in the plate, the wave reflection is built up of both shear wave and longitudinal wave. Then after these waves hit the next surface and divide into two additional waves on the reflection. This pattern is repeated over and over (Peter & Bernard, 2002).

The waves interfere with each other and provide the condition where certain resonant waves are created. These resonant waves, called bounded waves are a combination of both longitudinal and shear waves. These waves can be either symmetric around the center or asymmetric around the center. Lamb waves can travel through the total thickness of an object. Lamb waves propagate based on density, elasticity and the material characteristics (R. Abdul Rahim et al., 2007).

In addition, the frequency, substance thickness, the waves' mode and the material properties influence the Lamb waves velocity (R. Abdul Rahim et al., 2007). For creation of a wave with chosen frequency and thickness, Dispersion Curves can measure the velocity easily.

Dispersion Curves are very beneficial to create a Lamb wave. By Dispersion curves, we can understand the relation between velocity,v, thickness, d, and times the angular spatial frequency, k. From Snell's law we have:

$$\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2} \qquad (2)$$

2.2.8. Longitudinal Creeping Waves

A Longitudinal Creeping wave is created when a longitudinal wave is refracted acutely on the boundary of two semi-infinite objects. Then, the Longitudinal Creeping wave transmits along the border of those two objects with the velocity of the longitudinal wave. As the longitudinal creeping waves are traveling, they degrade very quickly. The reason is that the energy mode of the longitudinal creeping waves transforms to the shear waves during the traveling. It is noticeable that whenever a shear wave is created on the interface, the wave converts to SAW. The roughness of the surface doesn't influence the Longitudinal Creeping waves. In addition, these waves cannot be adjusted with the curved surface (Peter & Bernard, 2002).

2.3. The Notions of Reflection and Refraction at an Interface

Here we discuss about the encountering of the wave with a boundary condition. This issue can be more understandable with some examples of light waves behavior that we have faced a lot in the life. A partially submerged object in water that seems bent, the images in the pool water that reflect partially and our picture in the mirror are the tangible experiences of this phenomenon. To evaluate the ultrasonic material, we require to study basically the deviation or change of propagating ultrasonic waves induced the encountering of an interface. The ultrasonic waves' behavior in the interaction with a boundary can be presented as one of the four following states:

1. The reflection or/ and transmission is an understandable concept very close to what happens to a light wave when it hits a mirror or hits a parent material medium and reflects totally or partially.
2. Wave propagates along the boundary.
3. When the travelling waves direction changes, refraction happens. For example a semi-submerged object in the water looks bent
4. As the conversion mode when one wave type is converted to another wave type. It is also possible that one mode wave is turned to one or more modes of the wave.

If the wave refraction happens in different angles, the waves will propagate at different velocity so it will be in different modes. The Boundary condition is defined as the physical parameters that must be remained continuously around the interface. These parameters play an essential role in the equation, which governs the wave propagation. The boundary conditions of ultrasonic wave propagation consists the continuity of three items of velocity, pressure and the wave phase (Peter & Bernard, 2002). Difference of the phase can mean the phase relationship between pressure and the impedance velocity. The phase between pressure and velocity denotes that how intense pressure generates the velocity (Kim, 2010).

2.4. The Wave Phase

Impact on interaction of several waves occurs, when the sound pressure amplitude or particle displacement at any point of interaction will be the sum of two or several individual waves at that point.

There are three different possible interactions (Wikipedia):

- "In phase" so that there is no phase difference and the peaks and valleys of two identical waves are exactly the same, thus the result will be doubling the displacement of each particle.
- If the phase difference is 180 degrees (π radians), then the two oscillators are said to be in antiphase. If two interacting waves meet at a point where they are in antiphase, then destructive interference will occur. When that happens, the phase difference determines whether they reinforce or weaken each other. Complete cancellation is possible for waves with equal amplitudes "Out of phase" in which two waves eliminate the effect of each other.
- The last type is neither in phase nor out of phase. The resulting effect is the sum of the two individual waves at each point.

2.5. Acoustic Impedance

Acoustic Impedance (Z) is defined as below:

$$Z = \frac{P}{vS} \tag{3}$$

Where sound pressure (P) particle velocity (v) and the surface area (S), that an acoustic wave with frequency (f) is passing through that (Shull, 2002).

The sound waves behavior when it meets a boundary is fundamental of Ultrasonic Testing.

Differences in elastic properties or acoustic impedances of materials detect object changes such as voids, cracks, inclusions, coating etc. The importance of acoustic impedance is because of the following reasons:

- The difference between acoustic impedance of two materials' measures the acoustic and transmission reflection.
- Acoustic impedance is an effective parameter for designing ultrasonic transducers.
- The absorption of sound in a material can be evaluated by acoustic impedance.

2.6. Wave Attenuation

The phenomenon of attenuation happens where either amplitude of waves' propagation or the waves' energy, attenuate during the waves travelling. This diminishing of the energy happens as four mechanisms including of absorption, scattering, beam spreading and dispersion:

1. Absorption: Absorption is the basic waste of energy in the form of heat. In any mass movement, the motion energy of particles is converted to the heat energy. This energy conversion is very similar to the alternating energy of oscillating energy to the heat energy in slinky spring. Materials are periodically represented in the equilibrium position by the propagating waves. At the traveling distance, energy is reduced like what happens in damping or braking forces on the oscillating particles. Regarding$f = \frac{v}{\lambda}$, the waves with the higher vibration frequency have shorter wavelength. In addition, the higher vibration frequency leads to the higher displacement per length. Therefore, we expect that waves with higher vibration frequency result to the higher rate of attenuation.
2. Scattering: Scattering occurs because of the when traveling waves interact to the structure or material variation. A wave can reflect, refract and diffract and be in mode-convert, based on its propagation angle. These incidences happen when the wave hits the material variations or inhomogeneity. Materials discontinuities appear either in the material geometry or in the spacing in all over the material (Peter & Bernard, 2002).

Porosity, inclusion, the phase changes in some materials and the grain structure in wood, are the examples of material discontinuities. The change from one material to a composite material is a sample of variation of the material. In pure scattering, the energy of propagating wave is not transformed to heat. However, this energy is sent randomly to the different directions from the origin wave. The deviated waves are appeared as a grass (random noise). This energy is scattered according to the proportion of the size of scattered particles to the wavelength.

3. Beam spreading: Beam spreading is a geometric development of the wave front, which is not planar. In fact the true plane wave cannot exist because the wave sources are limited to develop. As we

mentioned before, not only the sound waves can change the direction as a reflection or refraction, they can also bend as diffraction. One of the diffraction properties is that the beam will diverge in touch of an obstacle edge. Second, is that the wave vibrates subsequently and severely in the developing wave field. Regarding the beam properties, the propagating wave can diverge or converge. Therefore, the beam spreading is also called divergence or geometric attenuation.

Considering the situation where a source generates the circularly divergent wave gives us a better understanding of beam spreading. By increasing the distance of traveling wave from the source, the wave displacement will decrease. We assume that the absorption affect is low and there is no scattering attenuation. By these assumptions the waves, which are generated one after another should have equal energy. By increasing the wave diameter, as the wave energy will diminish over the larger diameters, displacement will reduce.

4. Dispersion: Dispersion is a phenomenon that decreases apparent wave amplitude because of various wave-mode and also the different wave velocities. There are some ultrasonic methods that produce the waves from even one source and then propagate them simultaneously in more than one mode. Moreover, the different wave-modes, the different velocities also lead to the different transmit time between generation and detection. In the other word by increasing the distance of transmission, total energy will spread out in respect of time. Dispersion is essential for both guided modes and in the methods where is a very wild range of wave frequencies such as laser generation UT (Peter & Bernard, 2002).

2.7. Wave Characteristics

The ultrasonic waves are often defined as a harmonic (sinusoidal) waves, thus it will be understandable that any pulse is defined as a sum of harmonic waves. To study how a single cycle of a harmonic wave travels, we need to sign the pick of displacement on a cycle, and follow it as moves with the phase velocity, v.

A harmonic wave consists of these parameters:

- τ Is described, as the period of time is needed for a complete cycle of a wave traveling to a fixed observer.
- λ Is described as the wavelength. The required distance for one complete cycle of traveling wave

These two characteristics of harmonic waves, time periods and wavelength give several values including:

Wave velocity $$v = \frac{\lambda}{\tau}\left(\frac{m}{s}\right) \tag{4}$$

Linear temporal frequency $$f = \frac{1}{\tau}\left(\frac{cycles}{s}\right) \tag{5}$$

Linear spatial frequency $\chi = \frac{1}{\lambda}\left(\frac{cycles}{s}\right)$ (6)

Angular temporal frequency $\omega = 2\pi f \left(\frac{radians}{s}\right)$ (7)

Angular spatial frequency $K = 2\pi\, \chi \left(\frac{radians}{m}\right)$ (8)

Now we can rewrite the velocity of the wave in respect of angular spatial frequency and angular temporal frequency as:

$$\frac{dx}{dy} = \frac{\omega}{k} \quad (9)$$

Amplitude of a travelling harmonic wave is shown by A in the x direction is described as

$$(x, t) = A\sin(kx - \omega t) \quad (10)$$

Here the expression of$(kx - \omega t)$, is called the phase of wave function.

In this ultrasonic case study we indicate the particle displacement as an agreement by *u* instead of *y*. So the vector quantity of particle displacement, *u*, in scalar system in three dimensions ($\hat{x}$, $\hat{y}$ and $\hat{z}$are the unit vectors) is given by (Peter & Bernard, 2002):

$$\vec{u} = u_x\hat{x} + u_y\hat{y} + u_z\hat{z} \quad (11)$$

Now the position vector is gained by:

$$\vec{r} = x\hat{x} + y\hat{y} + z\hat{z} \quad (12)$$

As well as the vector quantity of the angular spatial frequency can be written as:

$$\vec{k} = k_x\hat{x} + k_y\hat{y} + k_z\hat{z} \quad (13)$$

$\vec{k}$, The spatial frequency vector or the wave vector indicates the direction of the phase velocity for example perpendicular to the phase front (Constant phase for a three dimensional wave in a plane). k_x , k_y and k_z are wave numbers, the spatial frequency in the x, y, z directions.

Spatial frequency multiplied by the position vector in three dimensions, results in a dot product vector as:

$$\vec{k}.\vec{r} = k_x x + k_y y + k_z z \quad (14)$$

2.8. Wave Pattern of Motion

We can describe the waves' behavior by consideration of the physical result of the forces, which are applied to the material. In addition, the vibration response in respect of the material properties gives an understanding about the waves.

Richard Feynman gives a pattern that briefly describes those physical events that cause a wave to propagate.

First the material particles (in the state of gas, liquid or solid) vibrate so the material density will change.

Second, after changing the density, pressure changes as well and loses its equality.

Third, this inequality causes to derive the material motions.

This pattern is like a cycle in which the last step pressure inequality provides the applied force in the first step to begin the cycle. In this part, the wave equation is defined to realize the wave behavior. The material properties impose the vibrational responses to the applied forces. By this way the wave motions are generated (Peter & Bernard, 2002).

3. Methods of Ultrasonic Testing

3.1. Introduction

In this chapter, we give a basic introduction of basic technique of ultrasonic inspection, as an important component of ultrasonic method. During this chapter the existing ultrasonic testing methods, the requirements and facilities will be considered. First, we are going to describe where transducer usage is in Ultrasonic Testing. Then we introduce the different type of transducers and their applications. A transducer is a device located on an object, used to convert a voltage pulse to an ultrasonic pulse and afterward transfers this pulse into the test sample. This is a fundamental method of the ultrasonic inspection. For signal travelling through the object and then transferring back again to the transducer, there are two methods that regarding the geometry and existing flaws, can be applied. The first one is "Pitch-catch method" that the signal is transferred from one transducer to another one. And the second principle is the "pulse-echo method" in which the signal is reflected back to the primary transducer. A Pulse-echo system is a transducer/receiver system, whereby a pulse transducer transmits the pulse into an object, it travels through the object and then after it will be received again by the transducer. During the time that the pulse passes through the substance, meets the existing defects and flaws, deviate from its direction and a small portion of the pulse without getting entirely to the end of the object will be reflected to the transducer/receiver. This reflection is smaller than the initial pulse and the end pulse (Peter & Bernard, 2002).

All these pulses which have been received; will be illustrated on the displaying device. The signal is then changed to an electrical pulse, and then can be read by an oscilloscope. To measure the principles of the ultrasonic attenuation spectroscopy, after an ultrasonic signal travels through an object, its frequency spectrum will be analyzed. This spectrum can be provided by the applications of the "Fast Fourier Transform" (FFT) for signal on time based ultrasonic signal. The "Through Transmission" (TT) and "Pulse-Echo" (PE) are two mode types that are commonly used for this purpose. In the case of (TT) mode, the transmitting transducer propagates waves through the whole body of object. Receiving transducer which is mounted on the opposite side of the object collects the reflected signals. Whereas in the case of (PE) mode as is mentioned before only the one transducer acts as both the emitter and receiver. Receiver collects the sound echoes, which are reflected from the samples interface of wall/air (Wrobel & Time, 2011).

Acoustics is about the generating of mechanical vibration by the objects' particles motion such as atoms in respect of time. According the way of particles oscillation, there are four different waves that propagate within the solid material. These four different principles of wave propagation include: shear waves, longitudinal waves, surface waves and in thin materials plate waves. An ultrasonic wave travels in liquid and gas medium along with all the sound waves communal as a longitudinal wave (R. Abdul Rahim et al., 2007).

3.2. Transducers

In this section, we discuss the real source of ultrasonic waves. The ultrasonic waves need a device to transmit them from the electrical or optimal signals. Ultrasonic transducers are what meets this purpose and plays both the roles of the source and the detector. It means that not only the ultrasonic transducer generates ultrasonic waves, but also is capable of detecting them by transducing the waves back to the electrical or optical signals.

There are many different types of transducers that represent the various methods for generating ultrasonic waves. Laser, as an optical method, piezoelectric and EMAT are the most usual methods are applied in the Ultrasonic Testing today.

The sensor's system is categorized into three different mode techniques:

- Transmission mode technique in which the changes of the transmitted acoustic wave is considered.
- Reflection mode technique, which measures the position of wave or a particle, reflected on an interface and as well as, the changes of their physical properties are determined. Refraction or diffraction

is another mode technique very close to reflection mode that considers the refraction and diffraction of a wave in a discrete or continuous interface in the specimen space.

- Emission mode technique, which considers and measures the intensity and the spatial orientation of an emitted radiation.

3.2.1. Piezoelectric Transducers

A piezoelectric material develops an electric charge on the surface to react the mechanical deformation. The direct effect of piezoelectric is the mechanical stress, which is applied to the output charge. This phenomenon gives a measurement of the quality of the material, which is employed as a receiver.

Indirect piezoelectric effect happens when a piezoelectric material is exposed to an electric field so a mechanical deformation develops. Moreover this effect consists of an input charge on the surface of the material that leads to an output strain (Peter & Bernard, 2002).

This phenomenon gives a measurement of the quality of the material, which acts as an ultrasound generator. The property of the piezoelectric material can affect the performance of this material as a receiver or generator. In the studies α and β are respectively the direct and indirect coefficient and they need to be compromised. So, the thickness voltage Δd and output voltage v_{output} are presented as:

$$v_{output} = \alpha \Delta d_{applied} \qquad (15)$$

$$\Delta \mathrm{d}_{\mathrm{output}} = \beta v_{\mathrm{applied}} \qquad (16)$$

Materials with higher α are commonly used to improve the reception. In addition, they simply generate the ultrasound at the higher voltage by pulse.

Pitch-catch element transducer consists of separate transducers, which are employed as receiver or generator (Peter & Bernard, 2002).

The piezoelectric crystals are one of the alternatives, which can be used to adjust the transducers’ function. How does a piezoelectric material generate the ultrasound? To find out the answer we can simplify the process by simulating a piezoelectric disk, which has electrodes at its surface.

As is shown in Figure 3.2.1.1, the periodic voltage pulse is applied to the both sides of the disc. Thus, as the disk contracts and expands, it starts to create an ultrasonic wave. The inverse process happens when an ultrasonic wave propagates through the disk. In this situation an electronic field among the electrodes is created while the disc contracts and expands (Peter & Bernard, 2002).The frequency that piezoelectric transducer is configured to, is defined as:

$$f = \frac{v_{crystal}}{2d} \tag{17}$$

The transducers can be classified based on five different features as following (Peter & Bernard, 2002):

- Contact, Immersion and Air-coupled Transducers
- Normal or angled beam
- Single or multiple elements
- Transducer face-flat (normal) or shaped (focused)
- Broadband or narrowband

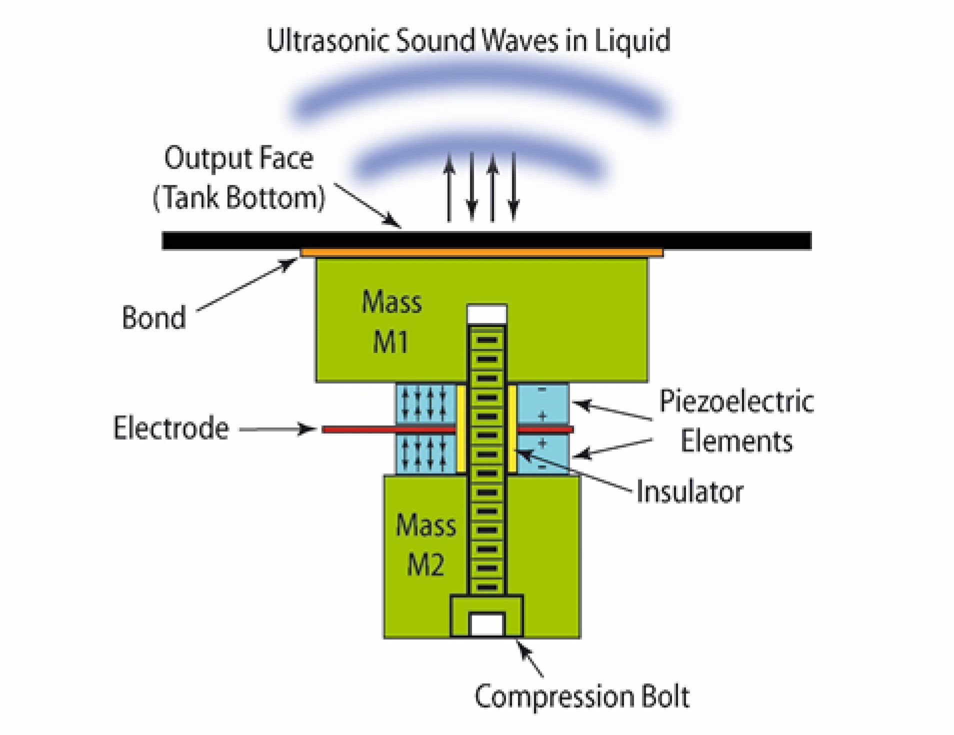


Figure 3.2.1.1 Typical Piezoelectric Ultrasonic Transducer (See ref list: Figure 1.1)

3.2.1.1. Contact, Immersion and Air-coupled Transducers

Contact transducers are in direct contact with the test object. However these transducers need some dry or liquid coupling. By this way, they are able to sufficiently couple the ultrasounds, which propagate from or to the sample.

Immersion transducers act in the scanning tank. In the scanning tank the transducers associated with the testing sample, are fully immersed within the fluid. Different encounter distances can perform scanning.

Air-coupled transducer by using a special layer comes over the high impedance mismatch between the piezoelectric crystal and air. This layer, called the impedance matching layer enables the transducer to send the pulse through the air to the specimen. The impedance matching layer should have mean impedance between the acoustic impedances of the air and transducer. The matching layer thickness should be considered for the best efficiency in maximum transmission. The ultrasonic beam that propagates through the mismatch layer/transducer interface has a phase difference due to the distance transmitted. The total phase difference is given by (Peter & Bernard, 2002):

$$\emptyset = 360^{\circ}\frac{2h_m}{\lambda} + 180^{\circ} \tag{18}$$

3.2.1.2. Angled Beam

The angled beam transducers contain a longitudinal normal beam transducer that is fastened to a wedge. In this arrangement, waves propagate at an angle to the face of transducer. The noticeable point here is that the wedge angle is not the same as beam angle, which is being created within the specimen. The angled beam transducers are usually labeled by their penetration angle. When a longitudinal beam travels through the wedge, multiple waves including longitudinal, shear and surface waves are created. Since the speeds of the shear and longitudinal waves are different, their reflections are received at different time. Thus, multiple waves can complicate features’ detection. To prevent this complication the wedge angles are designed as act between the first and second critical angle. By this way only a mode-converted shear wave is created (Peter & Bernard, 2002).

3.2.1.3. Multiple Elements

Multiple elements transducers are piezoelectric transducers that usually consist of two or more elements.
A dual-element transducer has separate transmitters and receiver elements placed in the same case. Its configuration makes a progressive analysis near the surface.
An array consists of certain normal piezoelectric transducers that work together. A phase array is result of constructive and destructive interference of the individual waves into an angled wave. This phenomenon occurs when the transducers are running either electrically or physically at times that are not considerably different (Peter & Bernard, 2002).

3.2.1.4. Flat (Normal) or Shaped (Focused)

Flat or normal transducers are devices for what we assumed before as a flat or planar face of transducer.
Shaped or focused transducers have two fundamental tasks: adjustment the probe face to the specimen contour and focusing the ultrasonic energy. Line and point are two current types of focusing. There is a finite spot size along with any geometric focusing. A depth-of-field where spot size is focused within can be confined by the finite spot size. This finite spot size limits also the accuracy (Peter & Bernard, 2002).

3.2.1.5. Broadband or Narrowband

The range of transducers' bandwidth and center frequencies is chosen according to a particular application. Narrowband transducers are employed for the material with high attenuation, where lower frequencies are needed. The narrowband transducers are weak receivers and excellent transmitters that give the most efficiency to the UT interference measurements.
Broadband transducers generate or receive a large range of frequencies. Unlike the narrowband transducers, Broadband transducers are great receivers and weak transmitters and often used in the measurements of the time-of-flight (Peter & Bernard, 2002).
There are three methods to drive a broadband transducer with a wideband frequency as below:

- The generation of the frequency sweep in which the frequency rises linearly in time.
- The generation of the tone burst which is a distinct frequency sweep that consists of a series of a few sine cycles. Each series has its own frequency.
- The voltage generation of the spike pulse in short duration is an interval like $(10^{-8} - 10^{-6})s$.

Since properties of the fluid, which contains solid particles change quickly in time, the measurements of dynamic processes can be challenging.

A positional distribution of particle concentration, form of different sized particles and flow dynamics influence on the process stability are examples of those changeable properties. To overcome these challenges both fast and broadband measurement are required. For this purpose the ultrasonic waves should be as short as possible to reduce the measurement time noticeably. The short voltage broad band among the three mentioned methods is the only technique that satisfies this requirement (Wrobel & Time, 2011).

3.2.2. Electro Magnetic Acoustic Transducers (EMAT)

An electromagnetic acoustic transducer is capable to generate and defect ultrasonic waves in electrically conducting sample. Since EMAT works without coupling media or mechanical contact, there is no need for surface preparation before testing. By this way, EMAT is able to move in the axial direction of testing object. This quality provides the possibility of taking data and differential measurements at different points along the surface of testing object. Another advantage of EMAT is to inspect rapidly those parts that surface contact is prohibited (Peter & Bernard, 2002).

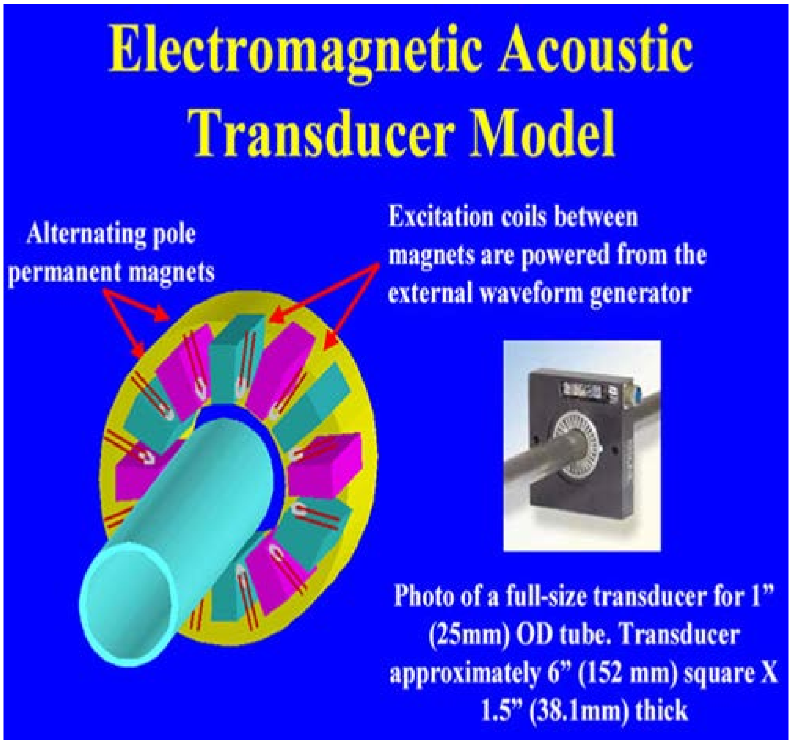
As a suitable feature, this magnetic ultrasound transduction is easily spread throughout most non-metallic barriers such as air, oxides, oil, painting, humidity and packaging material: paper, plastic foil, etc. Additionally it can readily be applied for different possible geometries and ultrasound modes such as shear guided waves, longitudinal waves, etc. (Rueter & Morgenstern, 2014).

EMAT can be employed in higher temperatures where immersion vaporizes and gaseous mixture of evaporated coupling causes decline or loss of coupling. By cooled air we can cool the transducer, without any impact on the ultrasound signal transfer (Burrows, Fan, & Dixon, 2014).

Referring to Figure 3.2.2.1, typical EMAT includes a permanent magnet and an induction coil. The coil induces eddy currents into a conductive specimen such as metal. Eddy current in the coil, which is parallel to the surface of conductive sample generates a magnetic field. By using permanent magnet vicinity to the material, a static magnetic field onto eddy currents flowing in the specimen, will be developed. Besides that specified field, a force will be created that acts on the material structure grid (Rueter & Morgenstern, 2014).

As the main problem, intensities of transmitted ultrasounds from EMATs are too low. For appropriate EMAT operation, only very small distances of “lift off” (less than few mm) are feasible. On the other hand, there are many application fields which increase lift off distances or ultrasound intensities for crude and large specimens such as heavy steel industries or prepackaged metal parts (Rueter & Morgenstern, 2014).

The next disadvantage is to decline the noise from the raw signal since particular techniques are needed. Moreover, permanent magnetic fields from EMATs attract ferromagnetic particles (magnetic and metallic materials). However, electromagnets can be used instead of permanent magnets. Such adjoining of particles can disturb the measurement or even can damage the transducer or specimen (Štarman).



Electromagnetic Acoustic Transducer Model

Alternating pole permanent magnets

Excitation coils between magnets are powered from the external waveform generator

Photo of a full-size transducer for 1" (25mm) OD tube. Transducer approximately 6" (152 mm) square X 1.5" (38.1mm) thick

Figure 3.2.2.1 Typical Electromagnetic Acoustic Transducer (see ref list: Figure 3.2.2.1)

3.2.3. Laser (optical) Method

Laser-based UT is one of the common Ultrasonic Testing methods particularly used in cases where non-contact methods are required, where either the ambient temperature is high or material cannot be contained with coupling. Transducers perform differently depending on whether the coupling is solid or fluid. Therefore, depending on how well coupling is maintained, it will restrict the speed of the scanning probes. Additionally laser-based UT is efficiently used for bandwidths and spatial resolutions and where there is a restricted access to contact probes (Scruby & Drain, 1990).

The laser based UT method has the capacity to play both the roles of generator and detector together or separately, in combination with other types of UT transducers. Although this transducer has low sensitivity, and it is delicate to vibrations, it is likely more costly because it needs skilled operators (Peter & Bernard, 2002).

An optical hummer is what excites laser (optical) generation of ultrasonic waves to make a high energy-pulsed optical beam. This beam is centralized to the object's surface. *Ablative* and *Thermo-elastic* are two processes in which optical pulses and object interact. Each of those processes has its own pattern for acoustic wave propagation through the material. A material's ability to absorb the energy and the energy density of the pulse, determine the excitation type at encountering of optical beam and object surface (Peter & Bernard, 2002).

In pulses with higher density of energy and absorbent materials, the optical pulse is ablated under the ablative process. In this condition, to create an ultrasonic pulse, a local explosion occurs on the surface and material is thrown out from the surface.

Contrary, at lower optical energy densities and/ or in object, which is less intense, excitation falls in thermoplastic type. In thermoplastic cases, the surface of material is heated very quickly by the optical energy. As the optical energy is released, the heated surface gets cold very fast. The corresponding pulse of material expansion and contraction produces ultrasonic waves.

Ablative excitation unlike to thermoplastic can cause some damage on a surface of an object. Two mentioned excitations are also distinct regarding the amount of energy, which is absorbed to wave, type of wave and the directivity patter of far field. There are different principles for detection and generation processes of the laser method. EMAT and Piezoelectric transducers can be employed to detect waves, which are generated by Laser. Unlike the detection processes of EMAT and Piezoelectric transducers, laser detection is not the conversed procedure of its generation process (Shull, 2002).

Figure 3.2.3.1 displays a comprehensive laser based system consisting of three units, i.e. excitation, sensing and control units. The Nd Yag pulse laser emits a high-power pulse laser beam. Laser is in the excitation unit and propagates the beam toward a target point, through the galvanometer. As a trigger signal is transmitted from the control unit, it activates the sensing unit. Then, in the sensing unit, LDV measures ultrasonic responses and sends them to the control unit. The control unit also transmits control signals out to arrange the galvanometers' motion. At the end, the post-processing and imaging of measured ultrasonic wave fields is performed in the control unit ('Sync' denotes synchronization).

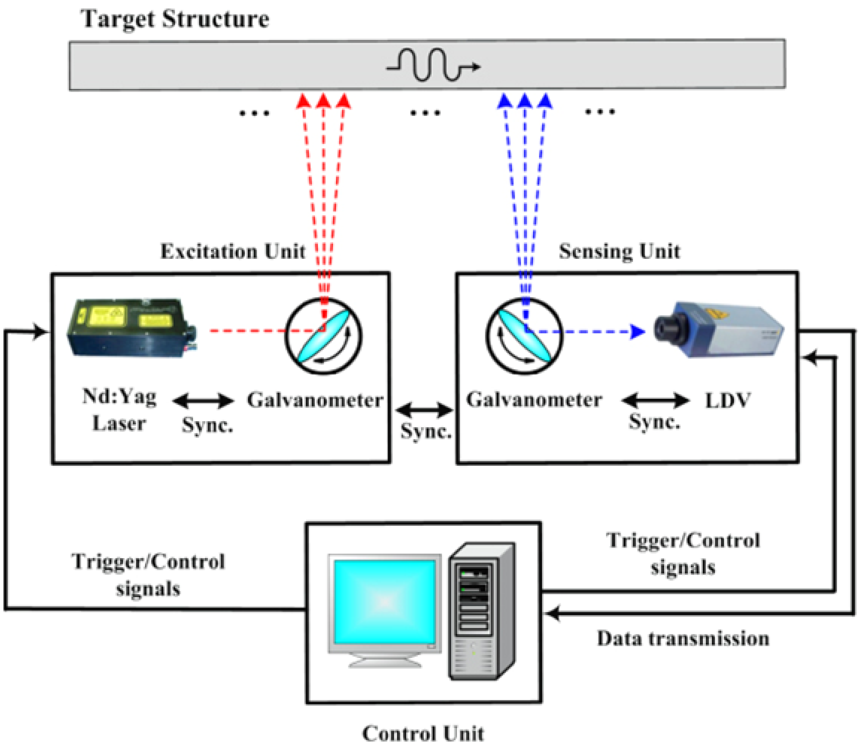


Figure 3.2.3.1 Schematic diagram : the developed system consists of three units, i.e. Excitation, sensing and control units (Yun-Kyu, Byeongjin, & Hoon, 2013)

4. Wave Ultrasonic Testing in Metal Pipe

4.1. Introduction

The Ultrasonic method for two reasons is very ineffectual in the air. First, there is a high mismatch between the impedances of air and the sensors. Second, the signals' energy is attenuated through the air (Scattered attenuation) and the signals do not enable to transmit through the pipe. Air-coupled transducers are the solution to avoid the mismatch between air's acoustic impedance and the sensors' impedance. In addition, it provides an air-free region to avoid the signal's attenuation. The arrangement consists of an acoustic coupling which is mounted between the pipe's wall and the transducers' surface to make a reliable transmission of the ultrasound. Different couplings can be selected based on short term or long term utilize. Araldites, Euro thane resin and epoxy resins are the examples for long-term utilization, which are without fillers. Silicon grease and axle grease are used for a short-term design. R. Abdul Rahim et al. (2007) in their research recommended the glycerin coupling as a short-term usage. A thin bead of coupling between the pipe surface and transducer is considered how it should keep the curvature form of the pipe (R. A. Rahim, M. F. Rahiman, K. Chan, & S. Nawawi, 2007).

4.2. Investigating Metal Pipe as a Conveyor

According to, DNV, 2010, rate measurement and inspection are carried out by the following two examinations:

1. Internal visual or external ultrasonic inspection over spheres for the identical thinning
2. Internal visual, developed external ultrasonic or radiographic inspection of the internal surface for local wall metal loss.

Reorganization of hot spots is necessary in all of these situations (DNV, 2010)

Guided wave system combined with other NDT techniques optimizes a corrosion assessment, without changing data quality.

As is shown in Figure 4.2.1 long range guided wave inspection is potentially able to screen a large area of pipe underneath or in the vicinity where the sensor is located at a single transducer position. Thus, waves propagate a relatively long distance (typically 180 meters) in the structure with minimal attenuation, which makes LRUT testing properly utilized for rapidly screening of pipe therefore is less time-consuming in comparison to conventional ultrasonic or eddy current methods (Cawley, Lowe, Alleyne, Pavlakovic, & Wilcox, 2003).

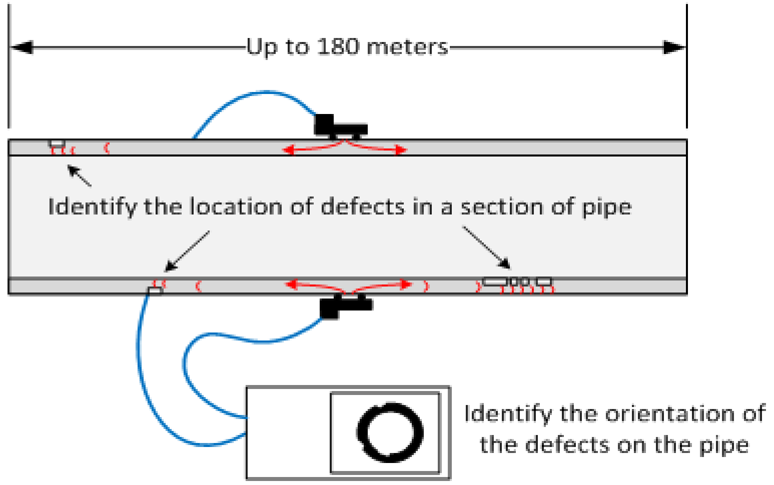


Figure4.2.1 Schematic Diagram of the Long Range Ultrasonic Testing (LRUT)

Principally the impedance of layers has significant effects on the way that ultrasonic waves propagate. Regarding the high difference in impedance among liquid and metal, utilization of metal pipe as a conveyor would be challenging in ultrasonic tomography (UT) process. In addition, there are some problems to produce a cross-sectional image of waves' reflections within an enclosed space, such as a metal pipe.

Due to high attenuation of ultrasonic energy and also the large impact of bulk waves on other type of pipes, usage of metal pipe is difficult as well.

For the solution of these problems, Abbaszadeh et al. (2013) experienced the propagation of both longitudinal and lamb waves in transmission mode in laboratory. The arrival time of waves to receivers and the receivers' amplitude has been emphasized. Basically, ultrasonic waves in longitudinal mode can travel easily from transmitter sensor to receiving sensor through a metal pipe, which contains low impedance liquid. Transmission method is very popular and extracts the concentration profile of the inside of the pipe by using the straight path signal. Straight path signal penetrates through pipe wall to inside of it. In an ultrasonic tomography system, which is measured in transmission mode, the received signal is expected to be entirely related to the basic signal. Because transmission mode amplitude is so weak on the receiving part it cannot impact the straight path line.

By increasing the frequency, the longitudinal wave is decayed quickly and cannot propagate for a long distance. This is a disadvantage of the longitudinal wave, which is responsible to detect the concentration data of the mixed liquid inside the pipe.

Lamb waves as a kind of SAW disturbs the receiving signal. By increasing the frequency the propagation of the ultrasonic Lamb wave reduces in the receiving part as is desired. Despite, the frequency increasing causesing a fast drop of straight path signal.

A suitable frequency of the ultrasonic sensors where metal pipe is employed as a conveyor of ultrasonic tomography should satisfy both longitudinal and Lamb waves.

The experimental structure is built up by a transmitter, receiver circuits and a metal pipe with a holding ring of sensors. The transmitters' duty is to produce the proper signal with the resonance frequency. The sensors have a wide beam angle to cover the wide area inside the pipe. They should have high amplitude voltage to overcome the attenuation effect of the metal pipe. Receivers reduce the noise effect and convert the analog signal to the digital (Abbaszadeh, Rahim, Rahim, & Sarafi, 2013).

4.3. Monitoring Regulations

Based on Recommended Practice DNV-RP-F116, monitoring consists of the measurement and collection of data. In addition, monitoring is able to provide information indirectly on the condition of a component or a system. The techniques that perform monitoring can include normally either on-line or offline measurements and also they can perform monitoring directly or indirectly.

In the monitoring process, we should first describe the purpose of the monitoring. In the next step it is important to save the acquiesced data. Then is the time of retrieving data and analyzing them.

The final attention is about documentation and reporting that includes comparison against acceptance criteria.

DNV-RP-F116 defines two types of monitoring as On-line monitoring and Off-line monitoring. Online monitoring represents continuous and/or real-time measurements of desired parameters. Off-line monitoring is normally based on subsequent analysis at e.g. a laboratory.

4.4. Long Range Guided Wave Ultrasonic Testing

Long Range Ultrasonic Testing (LRUT) is one of the most significant development and modification in ultrasonic NDT. Although this method has been taken apart over two decades, it has only recently become practical. LRUT is a monitoring technology that detects and analyzes metal loss features such as corrosion and erosion in pipes. This technology introduces low frequency bandwidth of ultrasonic waves that propagate along a structure while being guided by the enclosed spaces (such as a pipe).

Low frequency as an essential benefit of this technique, results from three occurrences that are seen subsequently (Yakovlev et al., 2013):

- The guided waves absorbency is low in the pipe material.
- For pipes in air, a small amount of wave energy leaks out of the pipe. The energy is entirely emitted down the pipe but its amplitude attenuation is still limited. This is because of the high acoustic impedance mismatch in an air-solid interface. (Alleyne, Pavlakovic, Lowe, & Cawley, 2001).
- The rate of pulse diffusion in respect of time is low (frequency is a function of phase velocity), owing to selection of a low dispersion mode of wave.

Although (LRUT) testing utilizes ultrasonic frequency sound energy as the inspection medium, it is fundamentally different from conventional ultrasonic testing. Long Range Guided Wave (LRGW) testing uses low ultrasonic frequencies compared to those used in conventional Ultrasonic Testing (UT). The frequency range used by LRUT is typically between 10 kHz and 100 kHz. Using higher frequencies is possible but it has an effect on the length of the structure, which can be inspected. It means that a higher ultrasonic frequency causes shorter inspection range. It should be noted that (LRGW) testing is a screening system not an accurate quantification system. Figure 4.4.1 displays a sectional image of metal corrosion that represents the output image of LRUT schematically.

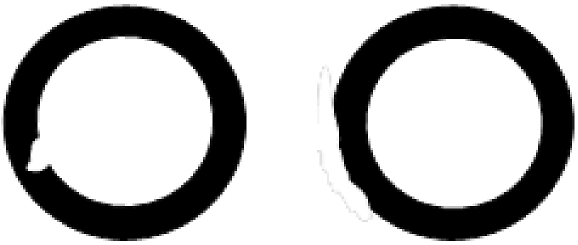


Figure 4.4.1 Pipe Loss Corrosion Section

According to DNV, 2010, normally there is a large scatter from measurements of wall thickness. The reason of this fact is induced from a natural inaccuracy of ultrasonic measurements, small variations in calibration from one inspection to the next, alterations because of operator and changes owing to non-repeatability in location. The corrosion-erosion resulted from potable water classes, at times stagnant conditions provoke sulphate-reducing bacteria (SRB). This condition does not belong just to bends and may happen in straight sections as well. This damage can be investigated by wall thickness measurements which are achieved by ultrasonic testing (UT) of the area (DNV, 2010).

DNV-RP-F116 in respect to corrosion, gives two definitions for direct and indirect techniques:

- Direct techniques are defined as measurements of the corrosion attack or metal loss at a certain location in the pipeline system by utilizing corrosion probes.
- Indirect techniques are defined as measurements of affected parameters on the corrosion. LRGW does not use direct measurement of the remaining pipe wall thickness (Veritas, 2009).

According to DNV-RP-F116 a non-intrusive monitoring contains an external technique that does not require access through the wall thickness. Moreover, it includes analysis of sample data obtained from the process stream.

The rate of corrosion dictates for how long any process equipment can be safely operated. A corrosion monitoring technique can be useful in several ways such as:

- It provides an early warning of probable changes in rate of corrosion

- It displays a relevant effect on the corrosion and also demonstrates the changes in trends that occur in the parameters of the process
- It monitors the effectiveness of the implemented actions to prevent corrosion, such as chemical inhibition.

4.4.1. Monitoring of Internal Corrosion and Erosion

DNV-RP-F116 classifies monitoring techniques for corrosion monitoring and sand management as following:

- Monitoring probes are categorized as Electrical Resistance (ER) probes, Weight loss coupons, Linear Polarization Resistance (LPR) probes and Hydrogen probes. ER-probes, LPR-probes and weight loss coupons normally are placed at topside. Any significant changes in the medium rate of corrosion and any increased uniform corrosion rate that might occur can be recognized by recordings from such probes. It will not be able to reveal local corrosion attacks.

- Field Signature Method (FSM) in which spools are placed at low points to measure local corrosion

- Sampling that is classified into two different types. Fluid samples is the first one and the second is debris samples which is collected by running cleaning or scraper pigs

- Devices for sand monitoring such as sand detection and monitoring probes, non-intrusive acoustic detectors (Veritas, 2009).

LRGW testing identifies the location of cross sectional area metal loss in the pipe; it does not register the geometry of the metal loss. This is a highly important point and the main reason for the use of LRGW as a screening system and not a detailed inspection system. The main benefit of LRGW inspection is that from one location it can screen relatively long distances of coated pipe, this means that only small portions of insulation need to be removed or small amounts of scaffolding used which saves time and cost. Another merit is that LRGW considers an inspection solution for unpiggable pipes. The usage of coupling is not necessary and there is no need to excavate the entire buried pipe (Sabet-Sharghi). If a “feature” is identified by LRGW inspection various focusing techniques can be applied to the ultrasonic waves to identify the location and the orientation of defect to enable a more detailed inspection with other technology (Abney,2015).

In order to offer an effective pipe process system, NDT service as Long Range Guided Wave inspection will have to be paired with another detailed inspection technology. The use of a simple ultrasonic probe or a more advanced phased array inspection device would be ideal. However, the phased array system will cost more than a simple UT probe. Once a detailed inspection of any damage has been completed a report will be issued to the operator including RSTRENG calculations (or similar) as to the maximum allowable pressure that a system should be subjected to. The report can also include recommended remedial actions such as removal of damaged sections of pipe and replacement with a new one. If the recommendations include replacement of sections of pipe Halliburton PPS provides the services to enable decommissioning, mechanical removal, preparation, welding by third party testing and reinstatement of the affected section(s) (Abney, 2015). Figure 4.4.1.1 below shows losses of metal pipe in 8 sections.

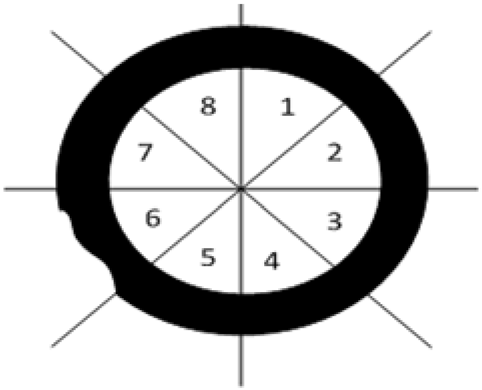


Figure 4.4.1.1. Cross-Sectional Metal Loss in Eight Segments

4.4.2. Existing UT Products to Investigate Corrosion

4.4.2.1. Olympus Ultra Wave LR

Long-range screening is typically used for assessment of pipe integrity. The importance of this technology is to detect corrosion at buried, insulated, coated and vertical pipes. It provides active and synthetic focusing and also is capable of producing F-scan color map, which displays multiple frequencies (OLYMPUS).

The Olympus Ultra Wave LR is one of the current industrial products that offers data acquisition unit with a wide frequency range, from 15 kHz to 85 kHz, bi-directional inspection develops up to 182 m (600 feet) of pipe's length. Pulse type is square wave, transmission mode is pulse-Echo and working temperature is between 0 and45℃.

As standard probe includes collar kits, covering pipe diameters from 2 in. to 24 in.

Guided wave technology is now widely accepted as an inspection technique and is designed according to ASTM international standards as an industrial standard (OLYMPUS).

Latest version of Ultra Wave LRT software includes advanced possibilities such as F-scan, Active Focusing and Synthetic Focusing (C-scan) that a brief explanation for each of them is given as below (OLYMPUS):

Acquisition Unit

The OLYMPUS ultra-wave LRT system as shown in Figure 4.4.2.1 consists of a 16-pulser acquisition unit and a frequency spectrum of 15 to 85 kHz. This is able to be regulated in 1 kHz steps for high resolution.

Decreasing acquisition time and data file size are performed by lower resolutions in software. For improving on-site efficiency, system uses two hot-swappable batteries (OLYMPUS).

Figure4.4.2.1.OLYMPUS Ultra-wave LRT Acquisition Unit

Probe Collar

The probe modules are usually sealed in a molded housing to enhance the probe resistance in harsh environmental conditions. Probes are designed in light-weight and compact profile to provide a better consistent contact and stability on the pipe surface within data acquisition as is displayed in Figure 4.4.2.2. Plates are coated by resistant stainless steel. In cases such as buried or heavily coated pipes, relatively qualified penetration power and inspection assurance should exist. Probe's flexibility and its portable bands are important to make it applicable in limited-access locations (OLYMPUS).

Figure 4.4.2.2. Probe Collar (See ref list: OLYMPUS)

F-Scan

Frequency plays an essential role in guided wave technology as a detection method. In Figure 4.4.2.3 you can see an F-Scan color map that belongs that to Ultra Wave LRT software represents the entire frequency range needed over the pipe inspected length. This color map performs quick analysis by selecting the optimum frequency. A shadowed zone on the F-scan displays the power curve low area (OLYMPUS).

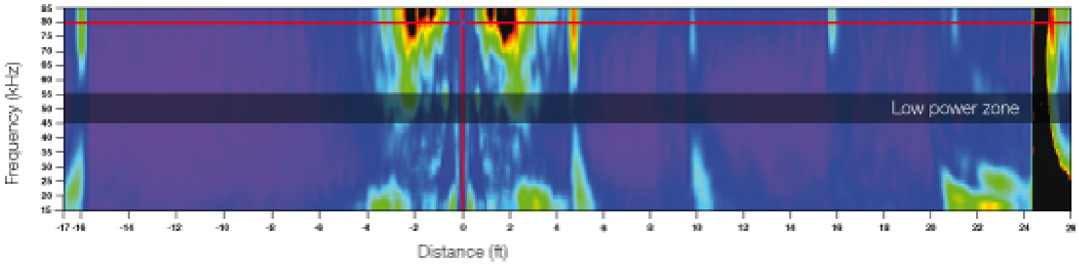
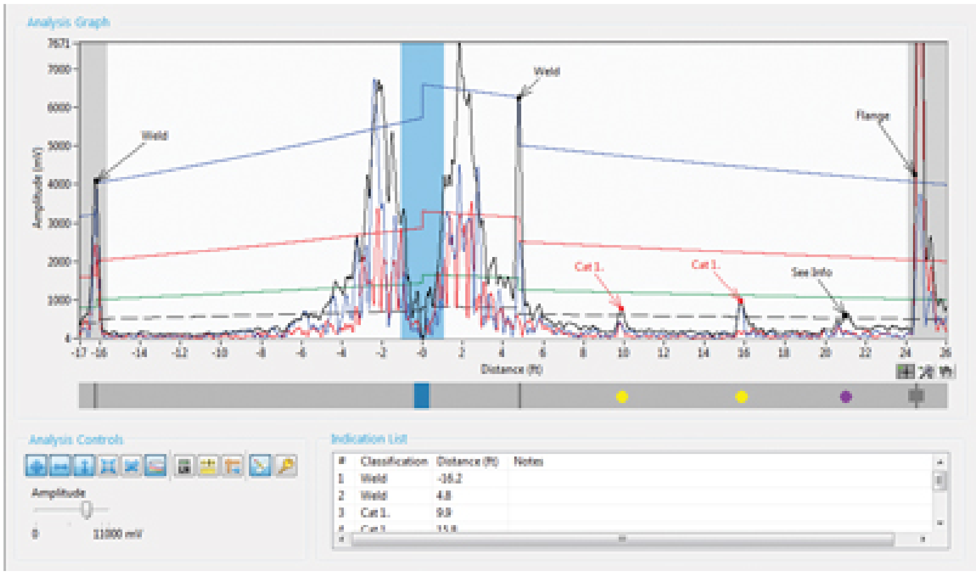


Figure 4.4.2.3. F-Scan Color Map (See ref list: OLYMPUS)

A-Scan Analysis

A-Scan is employed for detailed analysis so that for any selected frequency the related A-scan is used. This analysis method contains curve capabilities that exist in distance-amplitude correction (DAC), reflector annotations, and extra notations. Two separate sets of DAC can be matched for ahead and the opposite direction (OLYMPUS). In Figure 4.4.2.4 a sample of A-Scan virtual image is presented.



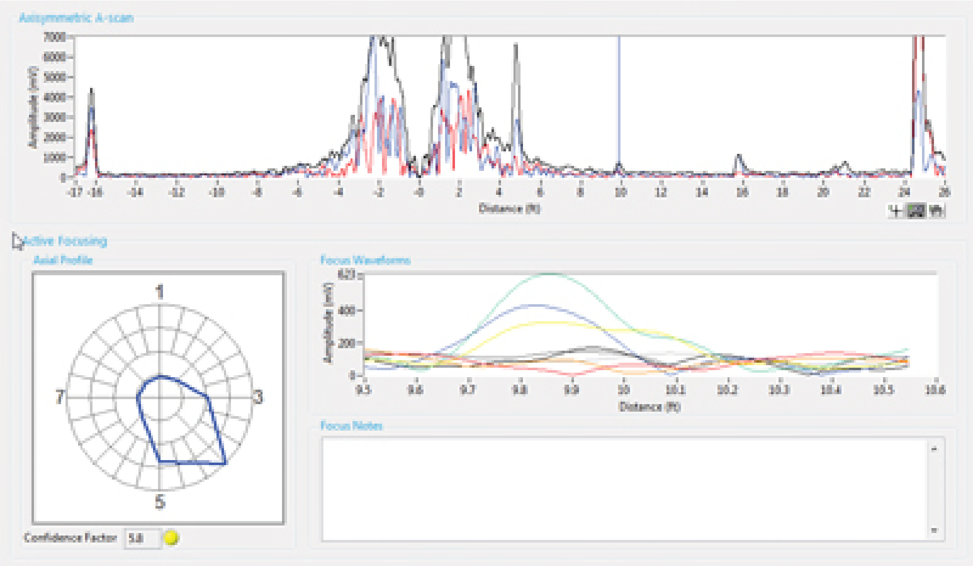
#	Classification	Distance (ft)	Notes
1	Weld	-16.2	
2	Weld	4.8	
3	Cat 1.	9.9	
4	Cat 1.	15.8	

Figure 4.4.2.4. A-Scan (See ref list: OLYMPUS)

Active Focusing

Active focusing offers a better quality assessment by delivering concentrated energy to a specific segment of pipe that gives better signal-to-noise ratio. To evaluate the pipe cross-section, for any specific length of a pipe, energy is focused at eight different positions surrounding the selected portion (OLYMPUS).

In Figure 4.4.2.5 an Active Focusing virtual image is presented.



Confidence Factor 5.8

Figure 4.4.2.5. Active Focusing (See Ref List: OLYMPUS)

Synthetic Focusing

Synthetic focusing is an offline tool that gives advanced analysis. According to the received phase velocity at a specific frequency, an image of unrolled pipe(C-scan) will be produced. This virtual image is capable of displaying entire area as displayed in Figure 4.4.2.6. Moreover, it estimates the axial position and peripheral extend of all defects (OLYMPUS).

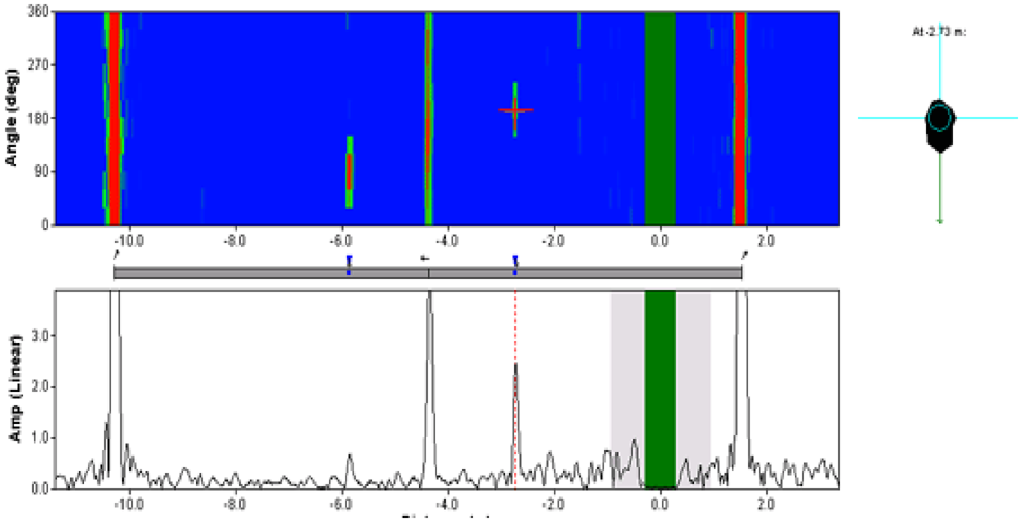


Figure 4.4.2.6. Synthetic focusing (See ref list :OLYMPUS)

4.4.3. Existing UT Products for Girth Weld Inspection System

4.4.3.1. Automated Ultrasonic Testing (AUT)

For over a decade Automated Ultrasonic Testing (AUT) increasingly has been employed to optimize the detection of flaws and sizing reliability. AUT offers the clear detection of planar defects, the improved reliability of vertical sizing, considering safety issues and environmental concerns. This technique provides accurate a detection method and increased speed sizing (at short inspection cycle time) with lower rejection rate. AUT performs real-time analysis from the smart output display. Additionally AUT gives electronic copy of inspection results. It demonstrates that scans are sector and linear electronically (Lozev, Spencer, Patel, & Huang, 2006).

AUT is constituted by a combination of different non-zonal approach methods such as following:

- Amplitude-based Pulse-Echo method (P/E) associated with shear wave, angled beam is very effective to detect the corner trap. However, studies indicate that beams with bigger angles about $50^{\circ} to\ 70^{\circ}$and frequency ranges of $4\ to\ 10\ MHz$ give more accurate measurement of through-wall sizing rather than beams with smaller angles as $45^{\circ} to\ 50^{\circ}$ at the same frequency.
- Pitch-Catch mode including combinations of tandem pitch-catch mode with dual-phased array (PA) -pitch-catch mode provides accurate detection with lowest noise level.
- Single-element multi-probes, which can be focused or non-focused along with phased array (PA) transducer and beam-fixed angles, are applicable for both sizing and cracking tip signal detection.
- PA P/E techniques perform relatively well detection by utilizing the sector scan technique. This technique drives the sound beam electronically through a range of angles. The sector-scan technique even in the case that a tip signal could not be detected, visualizes a good estimate of the through-wall extension of the crack.
- Time-based time-of-flight diffraction (TOFD) method will be useful to sizing fatigue cracks if through-wall extensions is less than 50% and well diffracted beam is received (Lozev et al., 2006). Small fatigue cracks less than 1.5 mm in height cause weak crack tip signal, inefficient measurement of strong corner trap signal and root geometry echoes.

Despite the profitable settings during scanning, smooth surface of fracture and the narrow opening of crack-tip create some challenges for detection and sizing of fatigue cracks. The reason is that smooth face of fracture acts as an acoustic mirror, which reflects back the ultrasonic sound beam with lower energy to the transducer.

Although tandem pitch-catch ultrasonic technique is suitable for fatigue crack detection and pitch-catch is applicable to measure the through-wall size, they both need angle combinations and comprehensive transducer spacing to perform an entire inspection. For the purpose of solving those problems, PA electronic (E) and Sectorial (s) scanning with multiple angles, advanced imaging and time-based diffraction techniques are employed (see Figure4.4.3.1.1).

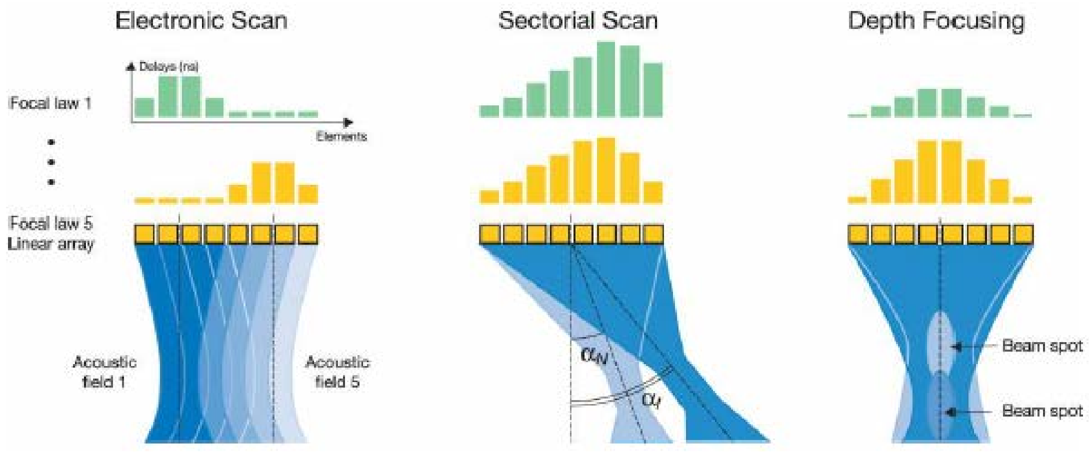


Figure 4.4.3.1.1 Illustration of Sweeping, Steering, Scanning and Focusing of the Beam

(Moles, Ginzel et al. 2002)

This technique is based on Engineering Critical Assessment (ECA) acceptance criteria with vertical height measurement and depth of indications. Data and reports of inspection are visualized on electronic support so that smart output display shows real-time analysis. In the last several years the Pipe-wizard system is one of the reliable existing industrial products that has been offered by Olympus. This system is applicable for both onshore and offshore pipeline constructions using automated ultrasonic testing (AUT) (OLYMPUS).

4.4.3.2. Phased Array Technology

A decade ago, phased array systems have been presented to improve information about the small defect and the increase of signal to noise ratio. Ultrasonic techniques should provide a signal to noise ratio of $4/1$ or better on the enforceable reference reflector (PRC-6510 Rev. A).

In this technique the ultrasonic energy is concentrated at a favorable distance along with the pipe from the transducer and at required angular position. Information about lateral extent of defect and the relation between size and amplitude is also available (Catton, Mudge, D'Zurko, & Rose, 2008).

The early AUT systems contained multi-probe systems including conventional ultrasonic probes. Normally, two phased array probes can replace more than 24 conventional transducers. Phased arrays generate and receive ultrasound by electronic beam, each element in the array by being individually pulsed and delayed is able to generate a wide range of angled beam and focal distances.

Phased Arrays ‘advantages in comparison with early AUT system are as following:

Position of each transducer does not need to be adjusted whereas loading a file performs Phased array settings. Placing proper parameters in the software optimizes Phased Array beams such as angle, focus, UT path, beam width, also causes more accurate sizing. Fewer moving parts of phased array system than AUT system provide steady inspection reliable scan. Scanner of a Phased Array is smaller and lighter than conventional multi-probe scanner and customized weld inspections, including multi-angle TOFD, advanced imaging and detailed inspections. There is an easier access and also it requires less coating diminution on each side of the weld (OLYMPUS).

The conventional multi-probe systems are limited in wall-thickness and pipe diameter. On the contrary, phased array is able to inspect almost any type of weld configuration.

Moreover, phased array technology offers the possibility of inspection in almost all zones simultaneously by the same probe. The actability of the fully weld coating with one probe on both side of the weld is provided.

Concentrating outside of the obstructions such as welds and defects can be challenging in this technique. Considering the effect on axisymmetric welds was attained by theoretical analysis such as three dimensional Finite Element Method (FEM) simulations and an experimental work. According to those studies, however penetration energy can be normally diminished by welds but few of them affect the focal location of phased array. The challenges of weld beyond inspection can be relatively solved by using the input time delays and also amplitude factors can be taken from traditional analysis (OLYMPUS).

Generally Phased Array technology is capable to steer, centralize and extend the ultrasonic beams and also provides the possibility of electronic scanning. Not only electronic scanning is quicker than Raster scanning but also can adjust angles so that the most efficient focusing detection will be performed.

Additionally this technique improves the sensitivity encountered defects by steering ultrasonic guided waves.

5. How does UT determine flow regime in multi-phase system?

5.1. Introduction

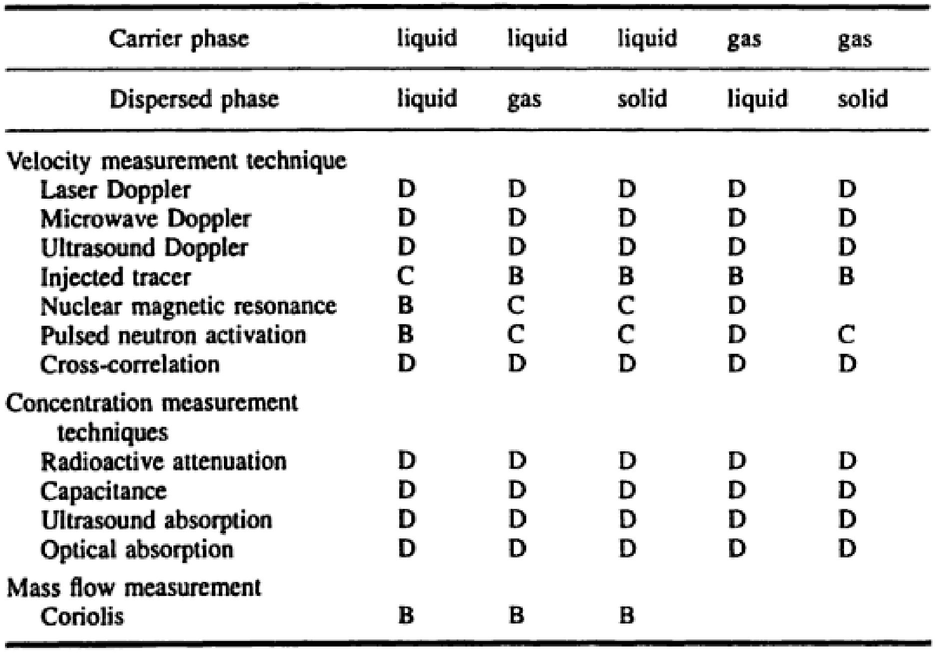
This chapter contains the characteristics of multi-phase flow and the most common detection techniques for flow measurements that will be explained. In this part, attention will be more focused on two-component flow. Following that, a brief review of different kinds of two-component flow and extensive information about the liquid-gas flow detection will be offered.

The most important issue about the multi-phase flow is that it should not be confused with multi-components flow. A multi-phase flow consists of separate phases that have interfaces between two materials (gas-liquid etc.) which alter in time and space. According to this definition an oil-water flow is classified as a two-component flow while a gas-oil flow can be defined as either a two-phases or a multi-component flow (Plaskowski, Beck, Thorn, & Dyakowski, 1995).
Six combinations of interfaces between media as shown in table 5.1.1 can be in the form of gas-liquid (GL), gas-solid (GS), gas-gas (GG), liquid-liquid (LL), solid-liquid (SL), solid-solid (SS) flows.

Table 5.1.1 Six Types of Interfaces between Different Media

	Gas	Liquid	Solid
Gas	GG	GL	GS
Liquid	LG	LL	LS
Solid	SG	SL	SS

As below, common industrial methods for deducible and direct measurements are displayed in table 5.1.2:



Carrier phase	liquid	liquid	liquid	gas	gas
Dispersed phase	liquid	gas	solid	liquid	solid
Velocity measurement technique					
Laser Doppler	D	D	D	D	D
Microwave Doppler	D	D	D	D	D
Ultrasound Doppler	D	D	D	D	D
Injected tracer	C	B	B	B	B
Nuclear magnetic resonance	B	C	C	D	
Pulsed neutron activation	B	C	C	D	C
Cross-correlation	D	D	D	D	D
Concentration measurement techniques					
Radioactive attenuation	D	D	D	D	D
Capacitance	D	D	D	D	D
Ultrasound absorption	D	D	D	D	D
Optical absorption	D	D	D	D	D
Mass flow measurement					
Coriolis	B	B	B		

Table 5.1.2 Common Industrial Methods for Multi-phases Flow Detection

(Plaskowski, Beck, Thorn, & Dyakowski, 1995)

Table 5.1.2 demonstrates whether each technique is especially sensitive to dispersed components, carrier or both. For carrier systems there are different ultrasonic Doppler flowmeters that deploy conventionally ultrasonic transmitters. This transmitter normally produces a fixed-frequency signal that is directed to the flow. Existing discontinuities of flow reflects this signal back to a receiver. Doppler shift principles can be defined as below (Plaskowski et al., 1995):

$$\boldsymbol{f_R - f_T = \frac{2 v f_T \cos\theta}{c}} \qquad \textbf{(19)}$$

In the equation above, Transmitted energy is shown by c and θ is an angle between the transmitted energy beams with the flow. The energy is transmitted from a source with constant frequencyf_T. Flows' dispersed components reflect back an amount of this energy which is received at a frequencyf_R. The difference between transmitted and received frequency is dependent on the velocity of carried component v (Plaskowski et al., 1995).

Based on equation 19, the relationship between dispersed component velocity and shift in received signal frequency is linear.

To generate a signal which has carrier modulated by the Doppler frequency, the transmitted carrier and received signal should be mixed, see Figure 5.5.1. A Band pass filter is used to eliminate the undesired noise and a separator is used to draw out the Doppler frequency.

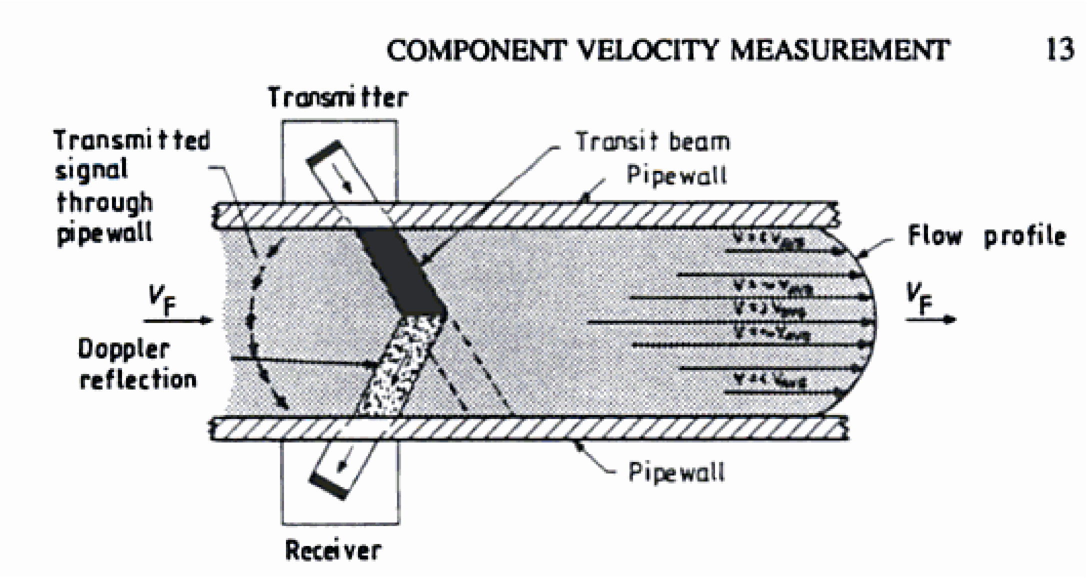


Figure 5.1.1.Doppler-effect ultrasonic flowmeter with separated transducers mounted in opposite side (Plaskowski et al., 1995).

The frequency range for the liquid can be an interval between 500 *kHz* up to few *MHz*'s. For the purpose of receiving ultrasound reflection at the lower frequencies like 500 *kHz,* the dispersed components must have a minimal diameter of $50\mu m$ (Plaskowski et al., 1995).

Doppler frequency is strongly dependent on the velocity of flow discontinuity in vicinity of pipe wall. The ultrasonic Doppler meter can be easily influenced by flow profile variation and the spatial distribution induced by discontinuities in the flow. The ultrasonic Doppler meter has usually poor precision almost in 5-10% of full scale. Calibrating the meter on-line can improve the accuracy of the most commercial ultrasonic Doppler.

Both fluid temperature and density affect the velocity of sound traveling within a fluid.

The temperature and density fluctuations of the carrier will cause a shift in the calibration of an ultrasonic Doppler meter. This problem can be solved relatively if the fluid temperature is measured and by adjusting c simultaneously in the equation of Doppler shift principles as temperature changing. The calibration alterations are usually unpreventable except in the case that the ultrasonic beams enter to or leave from a fixed angle to the flow. Permanent meters which are restricted to a pipeline will have a better repeatability of almost 1% of full scale that is achievable on less than 5cm pipe diameters (Plaskowski et al., 1995).

5.2. Ultrasonic Detection Techniques of Liquid-Liquid Interface

Rahim, Nyap, Rahiman & San (2007) presented UT principle of oil-water phase flow in horizontal pipelines. They deployed four pairs of sensors in and average output voltage for each of receivers and provided the results in layouts. The tomogram was produced by linear back projection algorithm (Rahim, Nyap, Rahiman, & San, 2007).

Back projection operation can be matematically displayed as following (Ref: Back Projection):

$$f_{b\rho(x,y)} = \int_0^{\pi} \rho(x\cos\emptyset + y\sin\emptyset\,, \emptyset)d\emptyset \tag{20}$$

According to geometric defination, the back projection easily spreads the sinogram backwards the determined image space along the projectiondirections(see Figure 5.2) .

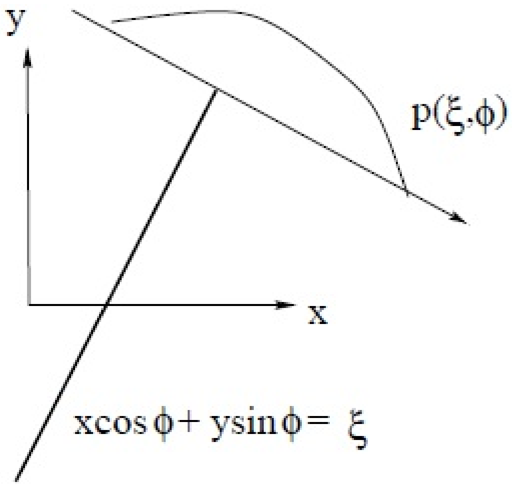


Figure 5.2. Geometrical Explanation of Back Projection

(See ref: Back projection)

The results indicated that as the oil percentage rises in the pipeline average voltage drops (Rahim, Nyap, Rahiman, & San, 2007). Another study in the same system was more concentrated on time-of-flight method used in UT system. Based on reports, the method can measure the oil-water interfaces in the oil productions (Steiner & Deinhammer, 2009).

5.3. Ultrasonic Detection Techniques of Solid-Liquid Interface

The detection of solid-liquid interfaces has been worked by using finite element method in COMSOL multi-physics software, to model two-dimensional ultrasonic propagation in vessel. The result of reconstructed image had high quality, which has been obtained by fast estimation algorithm (Wöckel, Hempel, & Auge, 2009).Detection of particle-liquid phase by UT system in vertical Poly Vinyl Chloride (PVC) pipes proved that the detection quality of smallest particles is related to wavelength. It means that if an obstacle blocks the wavelength, the information around the sensing area can be measured (Rahiman, Fazalul, & Abdul Rahim, 2010).

Wrobel and Time (2012), worked on liquid containing solid particles (20-40μm glass beads in water) by ultrasonic measurement. The study has been performed in high speed flow (1.5-2$^{m}/_{s}$), which can be challenging owing to turbulence existing in combination. Turbulence occurs in high percentage of close pipelines and it also creates essential effects on sound attenuation and distribution.

Based on superposition principle, the sound beams propagate quicker in the direction of flow. However, sound propagation in a solid particle-liquid flow with fractions higher than $1\%_{wt}$ was slower when the flow speed and subsequently turbulence intensity increased (Wrobel & Time, 2012).

According to superposition principles, the effect of temperature on the sound speed can be removed if sound propagation speed is determined simultaneously with the flow and in contrary it will be performed. In the other words, the flow velocity can be determined independently on temperature by using TTD methods.

By increasing temperature, sound velocity reduces in the acrylic wall. This event results in low consideration of the speed of sound travelling within the mixture. In steady flow speed where there is no high turbulence and temperature is constant, particles augment the speed of sound (Wrobel & Time, 2012).

Amplitude of signal decreases as there is a growth on the particle mass fraction. Signal amplitude reduces for augmentation of flow speed and flow turbulence (Wrobel & Time, 2012).

Sound attenuation in water normally reduces at higher temperatures. Although there is a small decreasing attenuation underneath temperature growth on the acrylic wall, it requires to be determined in “through wall” measurement (Wrobel & Time, 2012).

The air bubbles that are created between times in the flow containing solid particles do not effect significantly on the sound attenuation of suspension particles. In the other words, effects of air bubbles are bigger on frequencies in comparison with particles. However, as air bubbles lead to sound attenuation in all frequencies, therefore the prevention of the appearance of numerous air bubbles is important (Wrobel & Time, 2012).

5.3.1. Challenges of Ultrasonic Detection Techniques for Solid-Liquid Interface

Signal consistency and signal amplitude can be involved into some challenges by following events:

- Undesirable acoustic impedance of interface between transducer and water
- Non-efficient adjustment of the transmitter and the receiver setting
- Absence of an external pressing force on the transducers

Sound resonances are another important parameter in that they affect the determinations both inside the pipeline wall and the pipeline volume as well (Wrobel & Time, 2012).

5.4. Ultrasonic Detection Techniques of Gas and Solid Holdups in a Bubble Column

Ultrasonic computed tomography (UCT) was deployed to investigate the gas and solid holdups in a slurry column of bubble. Filtered back projection techniques (FBP) have been popular to achieve reliable results using integral measurement data. FBP is constructed from three processes of weighting, filtering and back-projection.

Although FBP techniques are very well known in tomographic reconstruction, they are still sensitive relative to noise. Processes, which are not modeled and are being produced and capture of real time are causing noise increase. The FBP's unacceptable results such as variations in the sensitivity of a detector, change of environmental conditions, transmission and quantization errors were revised by iterative filtered back projection (IFBP). IFBP was used to analyze distributions of gas and solid in slurry bubble column using UCT. In Figure 5.4.1 clarity of reconstructed images obtained from FBP and IFBP are shown (Utomo, Warsito, Sakai, & Uchida, 2001).

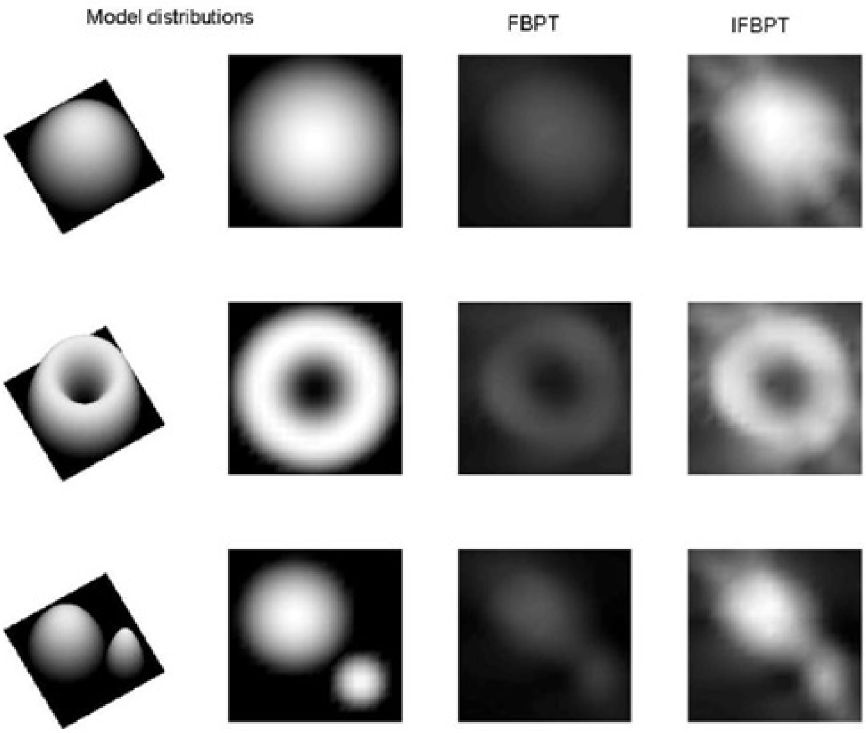


Figure 5.4.1. Reconstructed Images Obtained by FBPT and IFBPT UC

(Utomo, Warsito, Sakai, & Uchida, 2001)

5.5. Ultrasonic Detection Techniques of Liquid-Gas Interface

The key of tomography process is the recognizance of the interfaces between different components. For instance, various interactions can occur for gas hold-up in a liquid flow as below (Rahiman, Rahim et al. 2008):

- Scattering and absorption attenuation of acoustic wave
- Sound speed fluctuations in an inhomogeneous medium
- Fluctuations of amplitude and scattered field phase induced by physical characteristics of inhomogeneous filed

Supardan, Masuda, Maezawa, and Uchida (2007), in a research considered a column of methyl methacrylate with 16 cm diameter and 200 cm in height. The reconstructed images in figure 9.1 display the result of UCT system at a different height of the bubble column. The experiment work contained three parallel ultrasonic transducer arrays, that each array was configured non-symmetrically. They rotated 20° and concluded six pairs of ultrasonic sensor in parallel geometry. The bubble column image was taken by use of gas hold-up tomogram in the column. Distribution of gas-hold up surrounded the wall column center is higher than near the column wall. Figure 5.5.1 shows a half-blocked baffle that has been used to restrain the flow. UCT system for frequency of 2 MHz could sense the gas between 5.8 to 6.1mm in mean diameter (Supardan et al., 2007).

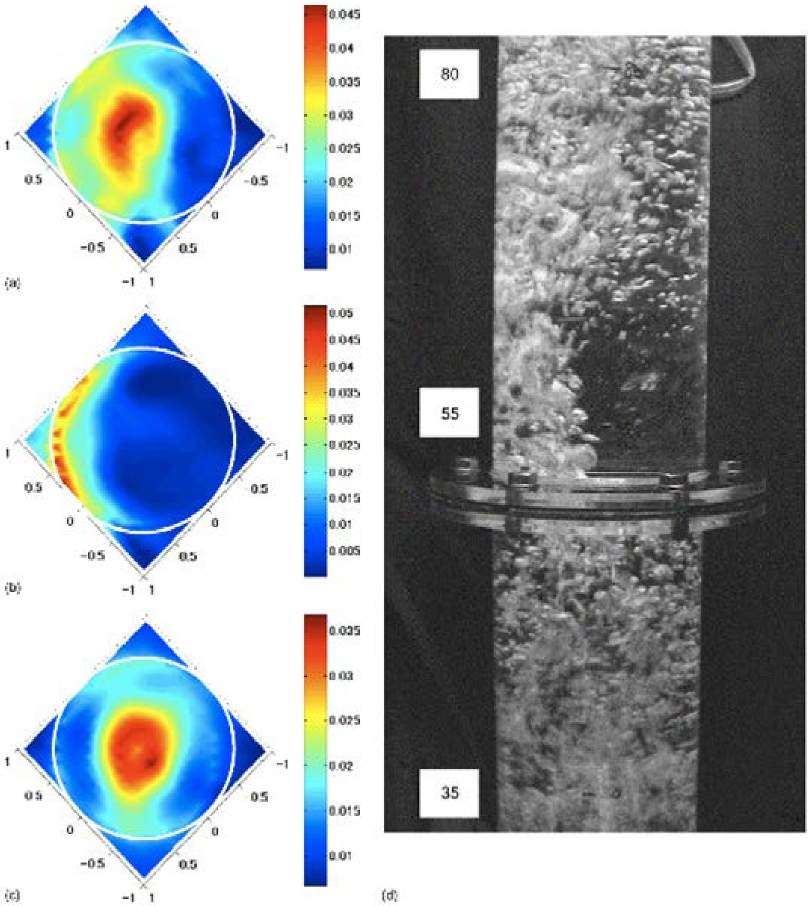


Figure 5.5.1.Distribution of Gas Hold-up in the Bubble Column

(Supardan et al., 2007)

The experimental work was comparison of 8, 6, and 32 transceivers at 40 KHz to inspect a water-gas. The results showed that the most optimal reconstructed imaging belonged to 32 transceivers set-up. The area error especially relating to small volume flow model that were quarter flow, 60% flow and annular flow was considerably large. This error was because of smearing effect in the applied Linear Back Projection Algorithm (LBPA) technique.

The projection causes blurring along the straight lines which have center symmetrical intensity distribution. This intensity distribution is based on the projection angle as the nebulous function is in reverse relationship with pipe radius (Zulkarnay, Mohd Hafiz, & Ruzairi, 2010).

Zulkarnay et al. (2010), in a water-gas phase flow projection used transceiver as an ultrasonic sensor. Transceiver in UT system can act as either transmitter or receiver and it contains few sensors instead of separate sensors. The separate ultrasonic transmitter-receiver sensor needs a large space to be mounted on the surface of the measured pipeline. Thus, pairs of the sensors were used, that each had the fixed function. This means that the sensors could play only the role of transmitting or receiving. Ultrasonic transceiver has a functioning merit compare to separate transmitter-receiver since it has the capability of vice versa function. It can act as a transmitter at one time and at the other time it works as a receiver .The efficiency of this dual functioning will be almost twice in comparison with the same number of separate transmitter-receiver. Therefore, measurements array provide relatively accurate tomographic images resolution (Rahim, 2007).

A gas-liquid interface noticeably modifies fluid flow both locally and globally. The interface presents a variety of behavior including length scales and forms based on the void fraction or the flow rate of mixed gas. Ultrasonic sensing can be considered as an alternative to detect the interfaces of two-phase systems in industrial applications such as pipelines, where there are severe restrictions for optical measurements. (Murai et al., 2010)

Dual-mode tomography is also fundamental of measuring flow rate in a multi-phase system. Flow measurements contain velocity measurement and void distribution or concentration distribution that can be obtained by tomographic techniques.

5.5.1. Velocity Measurements

A mixture can be considered as a single-component fluid if it satisfies all the usual equations. Calculation of volumetric flow rate in the case of *Pseudo-homogeneous flow* can be performed as same as the single component flow. By this way, for measuring the volumetric flow rate we determine a velocity profile across the pipe and then we utilize the cross-sectional average of profile velocity$\bar{v}$.

However, determining an appropriate velocity profile of two-component flow that is represented as either Laminar or turbulent would be more difficult than single-component flow.

If we assume that both components travel at the same velocity the volumetric flow rate Q according to *Pseudo-homogeneous* will be defined as following (Plaskowski et al., 1995):

$$Q = \int 2\pi r v(r)\, \delta_r \qquad (21)$$

Where *v(r)* represents the velocity of field and *r* is radius.

To calculate the Mass flow rate M we assume that two components of flow are mixed much more homogenously, meaning that there will be same density in any flow section of a mixture.

Mass flow rate, M, where , $\rho_{m,}$displays the density of the mixture will be calculated by (Plaskowski et al., 1995):

$$\boldsymbol{M = \rho_m A\bar{v}} \tag{22}$$

Velocity measurements data was achieved by ultrasonic tomography depending on time of flight. Process tomography is capable of measuring velocity distribution in dispread phase or the corresponding velocity between flowing phases. Ultrasonic tomography measures velocity field in vortex with two-dimensional flow (Hoyle & Luke, 1994).

This technique measures the difference in time-flight of ultrasonic impulses between two ultrasonic transducers where each transducer has alternate functioning as both receiver and transmitter.

Two following reasons cause the difference in the time of flight:

- The acceleration of ultrasound with the velocity field's component in sound propagating direction.
- Delaying that happens in the contrary direction.

The deference in time of flight is the foundation of a tomographic reconstruction (Dyakowski, 1996).

Ultrasonic interface detection is attributed to direct and non-invasive measurement. Studies in this issue introduced three ultrasonic detection techniques in their laboratory experiments as following:

5.5.2. Echo intensity Technique

Echo intensity technique depends on the amplitude information of reflected waves to investigate the interfacial position. Its utilization is to detect the interfaces which have length scales longer than the ultrasound wavelength (Murai et al., 2010).

For example the wavelength of a single ultrasound pulse in the bubbly flow regime can be normally compared to the bubble diameter. Thus, regarding to the incident waveform, the reflected waveform can be modified (Sboros, 2008).

As ultrasound reflects first-rate from gas-liquid interface, the reflection ratio can be calculated as below:

$$\mathrm{R} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2 = \left(\frac{\rho_1 C_1 - \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2}\right)^2 = \left(\frac{1 - \frac{\rho_2 C_2}{\rho_1 C_1}}{1 + \frac{\rho_2 C_2}{\rho_1 C_1}}\right)^2 \tag{23}$$

Where Z,ρ, and C denote respectively the acoustic impedance, density, and the speed of sound and the subscripts present the phases (Povey, 1997). When an angled beam transducer generates a beam with a divergence angle reflected wave received by transducer with dropped acoustic intensity, the acoustic intensity of the reflected wave reduces into the theoretical value. The effective ratio of the acoustic intensity is given by:

$$R_* = R\left(1 + 4\frac{l}{d}\sin\alpha\right)^{-2} \tag{24}$$

Where l identifies the distance from transducer to the interface and d represents the initial diameter of the ultrasound pulse beam (Murai et al., 2010).

5.5.3. Local Doppler Technique

As a single ultrasound pulse reflects from an interface, reflect waves will overlap with the incident. This overlapping occurs at half of the pulse length from interface and results to form of a thin standing wave layer. In such this situation the reflection ratio of this pulse from an interface will be 100%. This standing wave layer contains small particles or other reflector obstacles that do not produce Doppler shift regardless of velocity. Thus, by finding the negligible Doppler velocity, the measuring line of the interface can be detected.

Local Doppler technique is appropriate to detect the interface with large range of angles.

As frequency-domain data is applied this method does not depend on the distance between the interface and transducer location.

This technique can be challenging to distinguish the Doppler velocity from the real velocity of the flow around the interface. Another problem is the capability of this technique to detect the small interfaces like bubbles, especially when there is an interfacial curvature radius similar to standing wave length (Murai et al., 2010).

Both Local Doppler technique and Echo intensity are not successful for free-rising bubbles in quiecent water for three reasons (Murai et al., 2010):

- The rising bubble and flow of liquid are coupled so that bubbles never rise separately from liquid flow surrounding them.
- Bubbles lead to unstable interfacial deformation in a high Weber number regime that produces high-speed change .

5.5.4. Velocity- Variance Technique

Velocity-variance techniques are based on kinematics of the fluid flow. Following equation shows the kinematic interface condition (Murai et al., 2010):

$$\frac{\partial S}{\partial t} + v\frac{\partial S}{\partial y} = u \tag{25}$$

Equation above demonstrates the relationship between three parameters as below:

- Positions of interface ,*S*, along the measurement line
- Velocity component of flow ,*v*, perpendicular to the measurement line
- Flow velocity component, u, parallel to the measurement line.

The equation 23 the spatial coordinate perpendicular to the measurement line is denoted. This equation is employed to estimate the position of the interface, *S*, in computational fluid dynamic simulation of free surface flows. The position, *S*, is given to the two velocity-components, which are achieved from the motion of a non-turbulent, Newtonian fluid is governed by the Navier-Stokes equation.

Likewise, the free surface position can be measured from the velocity components obtained by ultrasound Doppler velocimetry.

$$\mathrm{S} = \mathrm{S}_0 \sin(\omega \mathrm{t} + \mathrm{ky}) \tag{26}$$

$$\mathrm{u} = \mathrm{S}_0(\omega + \mathrm{kv}) \cos(\omega \mathrm{t} + \mathrm{ky}) \leftrightarrow \overline{\acute{\mathrm{u}}^2} = \frac{1}{2}(\omega + \mathrm{kv}) \tag{27}$$

The variance of velocity components can indicate both the interface spatial appearance and the temporal change in ultrasonic beam direction. The larger temporal and spatial changes of the interface cause to the higher velocity variations. Utilization of this principle is to identify the interface in a periodic interfacial flow such as plug and slug flow in pipes.

For instance, we explain the case that in a turbulent interface the interfacial waves are shorter than the origin ultrasound wavelength. In such a situation, diffusion of the reflected pulse happens in the way that pulse is no longer propagating on the straight path. This is the right time that to employ the use of velocity-variance techniques.

These techniques can develop merit of ultrasonic pulses in the gas-liquid interfaces that transfer both passively and actively in two-phase flow. The echo intensity technique is very applicable where the changes of inclination angle of gas-liquid interface in respect of the ultrasound wave planes are negligible. Using free travelling waves has proved it.

The Local Doppler is very useful in the case that there is a wide range of interface angles and turbulent interfaces such as slug flow in pipe. By using the low Doppler velocity layer it can measure the complex interface forms as long as the interface is transmitted passively in the flow.

The velocity-variance is another way to detect interfaces of periodic interfacial flow such as slug flow. The appropriate usage of this method is where the periodic interfacial flow such as slug flow exists. This technique requires the temporal statistics of the Doppler velocity to extract forms of interface that match with real forms obtained using high speed imaging (Murai et al., 2010).

5.6. Ultrasonic Detection Techniques for Hydrate

The flow assurance issue on hydrate formation is one of the recent concerns in the oil and gas industry.

Gas hydrates are ice in the crystalline shape that is usually composed in inaccessible locations of pipeline. Hydrate crystallization is constructed of a mixture including gas and water molecules which are trapped in a restricted space. This phenomenon occurs under high pressure and low temperature conditions.

Water molecules as a host make hydrogen bonding with holes to create the inconstant crystalline lattice structure. The gas molecules as the guest molecule fill in these holes and by this way a solid gas hydrate is created.

Blockage and motion of hydrate plugs in the pipeline at high velocity can result to pipeline disconnection. The pipeline blockage induced by hydrate can cause some economical and personel hazards in oil/gas pipelines (Md Zain, Yang et al. 2005).

Certain parameters, such as size and type of the gas molecules, turbulence grade, water history and contamination can affect the hydrate nucleation.

Hydrate crystallization can be signed by four values including amplitude, velocity, frequency spectrum and phase shift. Study of Md Zain, Yang et al. (2005) has been proved that the changes in amplitude and spectrum as compared to variation of temperature and pressure are slightly constant. In contrast, amplitude and spectrum can be affected by particles feature in solution based on sound energy attenuation. In small amount of hydrate nuclei, velocity is more influenced by temperature comparing to nucleation.

First aqueous solution was sucked from the testing cell to create a vacuum then gas was injected to the cell at a desired testing pressure.

To keep the process within hydrate forming conditions, the temperature of system was decreased directly.

The ultrasonic method has been used for detecting the initial hydrate formation according to amplitude and Fast Fourier Transform (FFT) analysis. Thereafter, online monitoring of hydrate was utilized of the purpose of increasing hydrate's dissolution. Hydrate particles vary the water structure which is objected to remain in water phase and they desire to move through the produced fluid system. The hydrate particles were investigated and they might be separated from the other solid particles.

The detection system was composed from a Pulser /Receiver technique including two ultrasonic transducers with 1MHz frequency. The Pulser and receiver were mounted at two ends of a cell. Digital Storage Oscilloscope (DSO) was the virtualizing solution for waveforms and outputs. The experimental work was under 5800psi pressure and cooling system between -5℃ to 50℃ controlled the temperature.

5.7. Challenges of Multi-phase System Detection

The amplitude of reflected wave, which is induced from a single ultrasound pulse reflects off a liquid-gas interface, depends on the comparative acoustic impedance of two media. There are large different acoustic impedances in most gas-liquid combinations. Therefore, as long as the reflection is one-dimensional, the amplitude of the reflected wave is retained.

The main difficulties of ultrasonic sensing of liquid-gas interface are in varying interface condition. Where there is two and three-dimensional reflection and the amplitude changes with the interface condition in a very completely manner (Murai et al., 2010).

One of unfavorable limitations of multi-phase system is relatively slow speed of sound in ultrasonic computed tomography (UCT) (Supardan et al., 2007).

In Ultrasonic Doppler although enhancing the operating frequency provides the opportunity to detect the smaller scattering centers, it results in drop of transmitted signal penetration.

There are some limitations to develop the ultrasonic Doppler to gas carrier systems. For example, effective energy coupling achieved from the ultrasonic transmitter through the gas flow is one of the main problems. Although for solving this problem source frequency of about 40 KHz is useful, wide beam angles in such a situation causes some problems with the concept of measuring volume.

5.8. Advantages of Ultrasonic Sensing in Flow Measurement

The non-invasive nature of ultrasonic sensing is superior relative to optical and electrical probing, which needs an invasive submersion of sensors into the flow. Another merit is the possibility of easy handling ultrasound in comparison to X-rays or electric capacitance tomography. Moreover, ultrasound provides a direct detection of the local interface position from the reflected wave whereas computer tomography uses data from along the whole of the signal path (Murai, Tasaka, Nambu, Takeda, & Gonzalez A, 2010). The ultrasonic tomography system provides an essential inspection by flow inspection and imaging. These days, UT is applied widely to inspect chemical mixtures such as liquid-liquid, liquid-solid and liquid-gas systems (Wahab et al., 2015).

6. Discussion

6.1. Introduction

This thesis addresses the reader to the following subjects:

1. Introduction
2. Ultrasonic waves
3. Methods of ultrasonic testing
4. Wave ultrasonic testing in metal pipe
5. How does ultrasonic tomography determine flow regime in multi-phase system?

The extensive scientific literature is the foundation of the work that has been accomplished.
This section has attempted to present a comprehensive and authentic brief statement of the ultrasonic technology for pipeline detection. Additionally, based on the studies have been carried out in recent decades; the reliability of the available methods is discussed. For this meaning both theoretical and experimental aspects of previous works is considered with offered references.

5.2. What do we know about ultrasonic tomography system?

The ultrasonic tomography system is made up of four principal parts which are displayed in figure 6.2.1. First is the hardware which is generating a pulse, then the generating pulse is amplified and the amplifying pulse is propagated (Abbaszadeh, Rahim, Rahim, & Sarafi, 2013).

Detection is the second step that the propagating pulse detects the flaws or in the other words reflects back from the metal loss such as corrosion or weld girth. Pulses encountering the flows' interfaces or other discontinuities can also reflect back or lose their energies. In the next step the reflected pulse is received by sensors (hardware) which are mounted in the vicinity of pipe.

In the software part, the pulse is collected in the acquisition and reception part. The digital data is gathered to construct the cross sectional image of the pipe by using different algorithms (Abbaszadeh, Rahim, Rahim, & Sarafi, 2013). At the end, data is interpreted, images are evaluated and data can be quantitatively assessed.

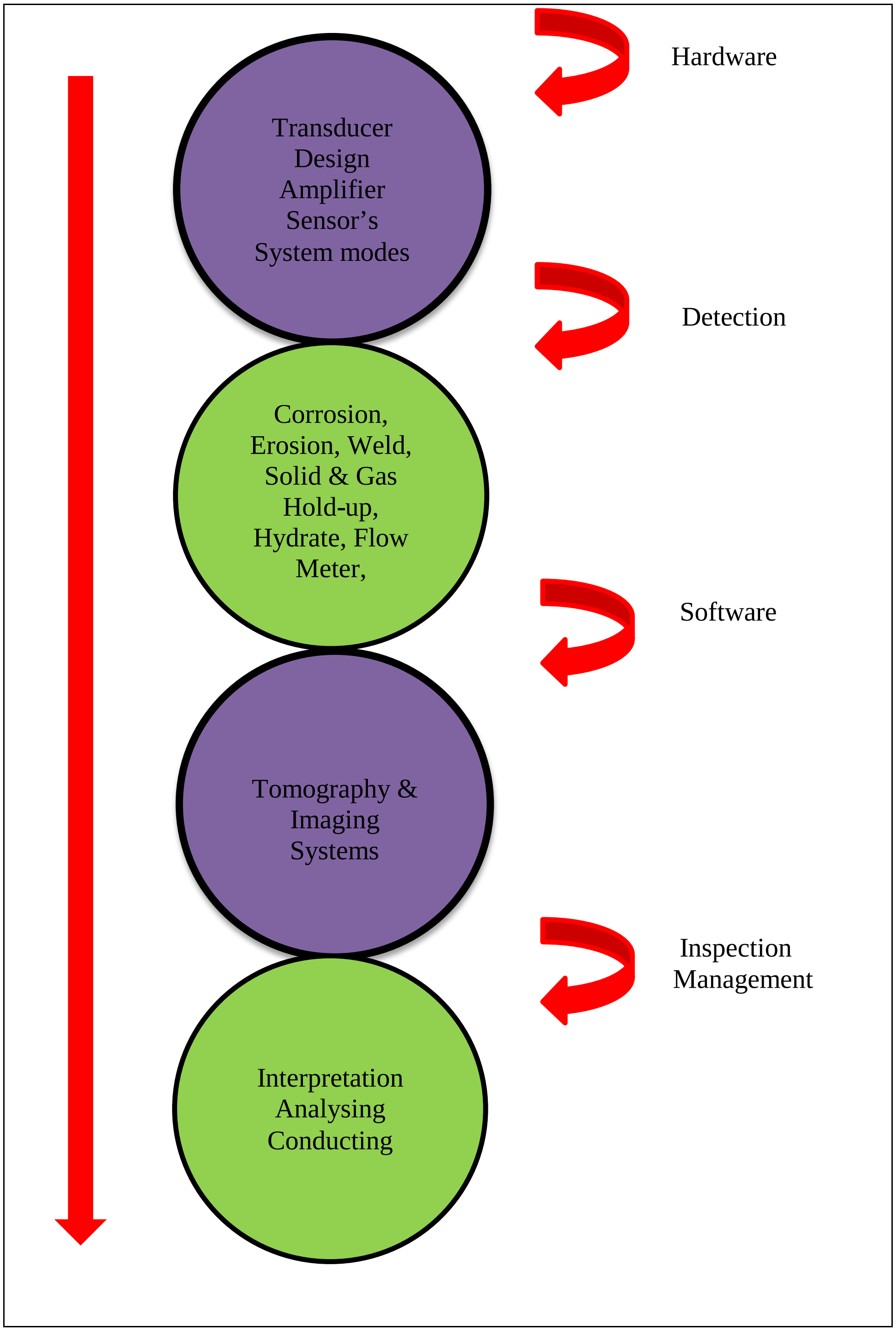


Figure 6.2.1 Knowledge about Ultrasonic Tomography System

5.3. What are the ideal Methods?

The introduction confirms that the industry visibly requires satisfying the demand for a worldwide pipeline’s full inspection. The importance of detection is to protect the pipelines from the challenges such as third party damage, environmental incidents and material destructions created during operation. Subsea pipelines defections, flow measurements and flow blockage are particularly the key challenges we may encounter in this field.

Deficiency of precise detection methods enhances those challenges. Although Ultrasonic Testing creates some challenging limits on the technology development, such a method will most probably result in a reduction of time-consumption and affordable technique to inspect pipeline.

Valid experiences indicate that the UT methods for fully detection of pipeline, work feasibly. Despite, the methods in some cases have limitations to inspect accurately the pipe in the long length of pipeline.

The ideal ultrasonic method reduces absorbency and causes the minimum wave attenuation. In addition, it should be generated as an adequate strong signal to be able to discover very small defects such as tiny fatigue cracks. A desired ultrasonic tomography system is capable of providing a fast screen imaging to decrease the time consuming.

Moreover, it determines the best time for pigging. Demanded UT method should be able to detect unknown amount of different types of residual along the pipeline wall.

This research study represents the UT limitation that provides demanding challenges for further investigations.

5.4. Existing Ultrasonic Methods for Detection of Pipeline

There is no favorable and accurate ultrasonic method which provides the synchronically demands of two following issues:

- Relatively long distance inspection of pipeline and its content
- A desirable clarification tomogram with precise quantification

Currently, a combination of different methods is being applied to approach to both aims of quantitative measurements and long distance inspection. For instance, the implemented combination of methods for demanded weld inspection which have been discussed in section 4.4.3.1.

For ultrasonic testing of a pipeline, the following procedure exerts (see Figure 6.4.1):

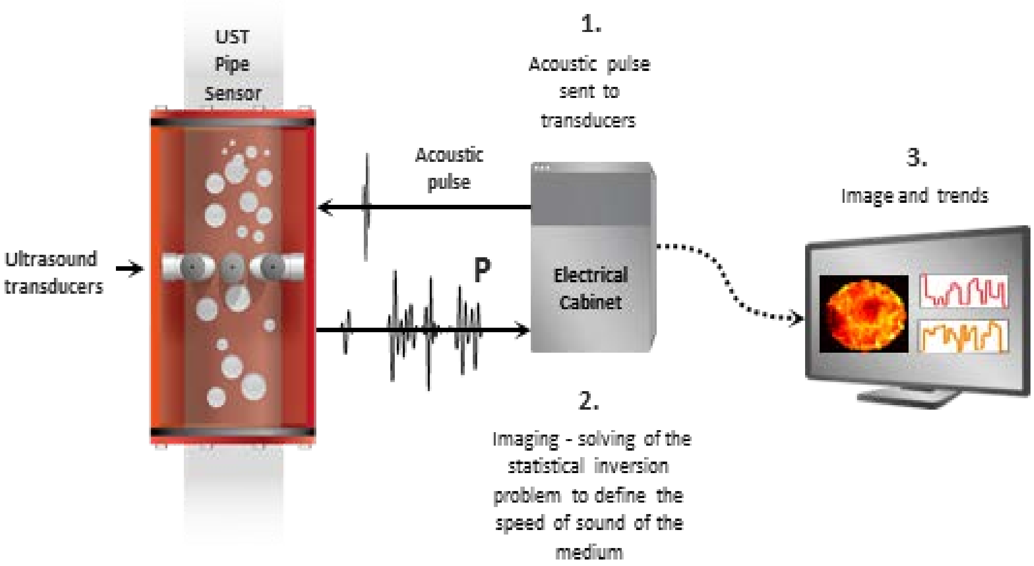


Figure 6.4.1 Schematic diagram of : the developed system consists of three units, i.e. Ultrasound Transducer and UST pipe sensor, Electrical Cabinet, Image and Trends

(See ref list: OLYMPUS)

5.5. The applicability of Ultrasonic Methods

The applicability of Ultrasonic techniques in different case of detection of pipeline defects, measurements of flow interfaces and hydrate detection must be considered by the subsequent issues:

i. Which parameters effect the transducer design?
ii. What is the maximum length of pipeline that can be inspected?
iii. What is the significant interval of signal frequency that can be applied?
iv. What is the appropriate angle for the generating signal?
v. How well coupling is maintained and what materials can be utilized as a long term coupling?
vi. Can the technique be used in pipelines with a large internal diameter?
vii. What effect does the pipeline material have on the technique?
viii. How is the precision and sensibility of the technique in monitoring and quantification system?
ix. Is the method capable to detect the size of each obstacle or defect?

5.6. The Advantages and Disadvantages for Existing Ultrasonic Inspection Methods

A brief evaluation of the most competent methods have been introduced and discussed in sections 4 and 5. In this section for the purpose of providing a concise overview, advantages and limitations based on the most proven methods are illustrated; see Figure 6.6.1 to Figure 6.6.4.

5.6.1. Long Guided Wave Ultrasonic Testing

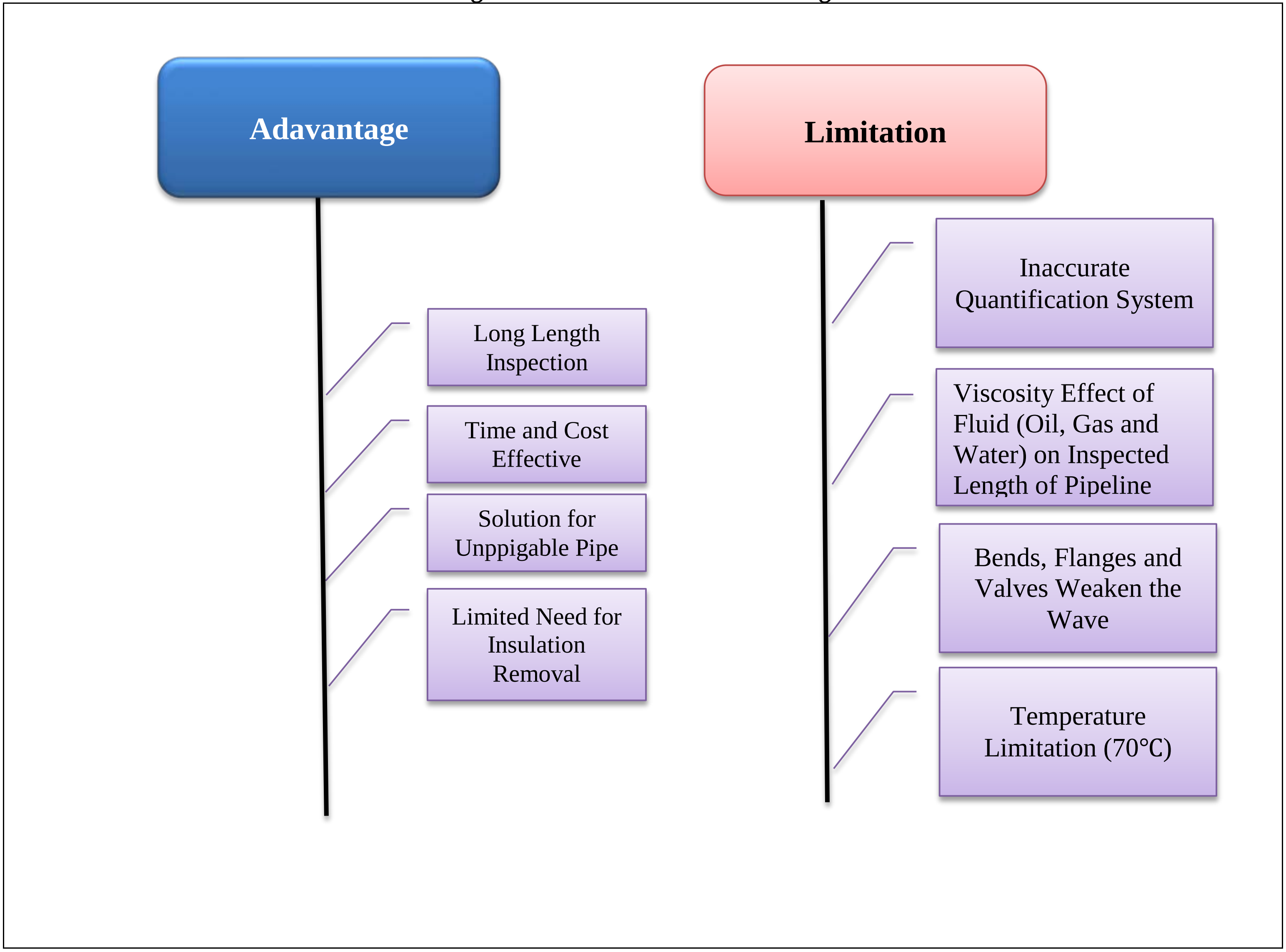


Figure 6.6.1 Consideration of Long Wave Ultrasonic Testing

5.6.2. Automated Ultrasonic Testing

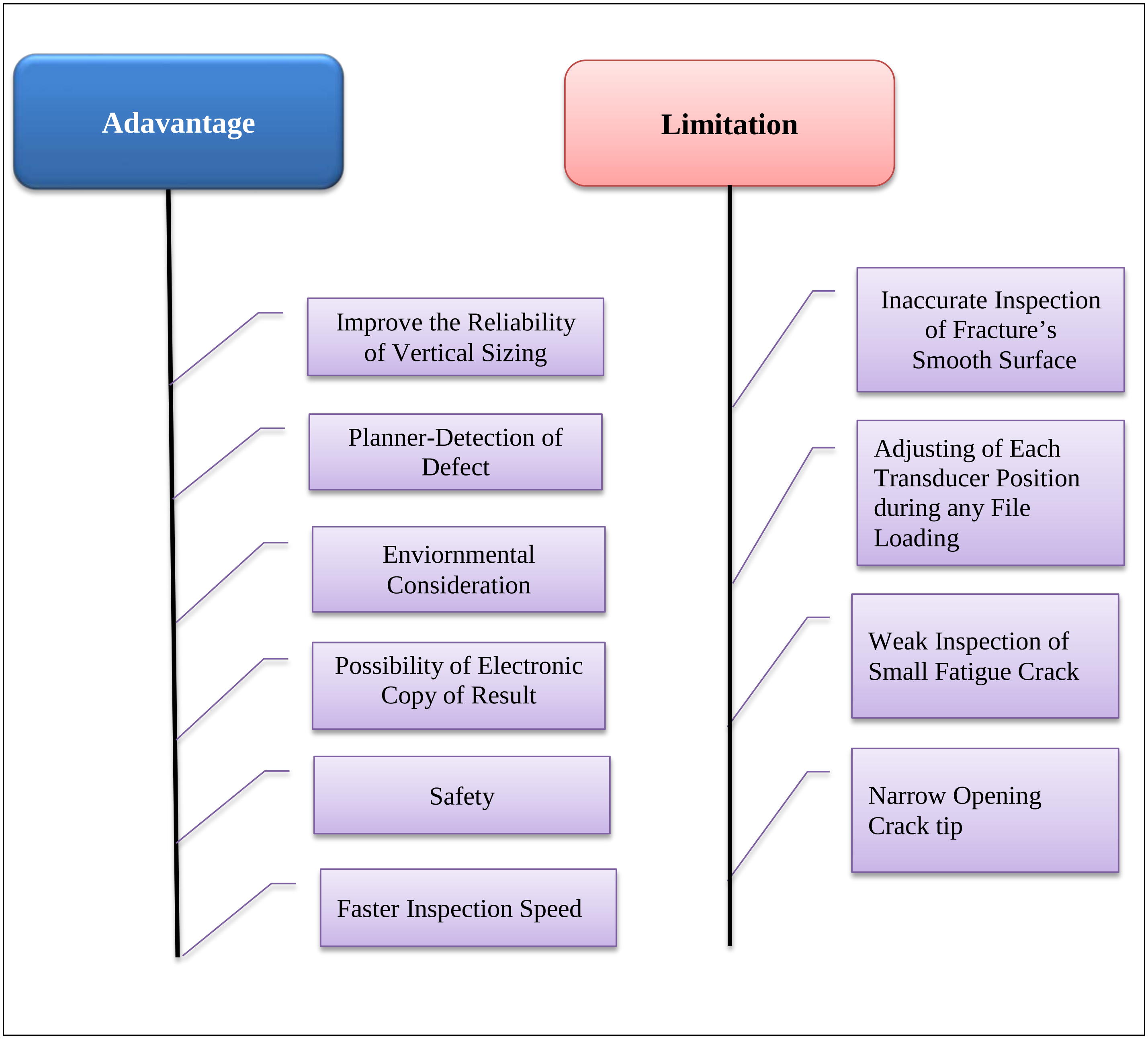


Figure 6.6.2 Consideration of Automated Ultrasonic Testing

5.6.3. Phased Array Technology

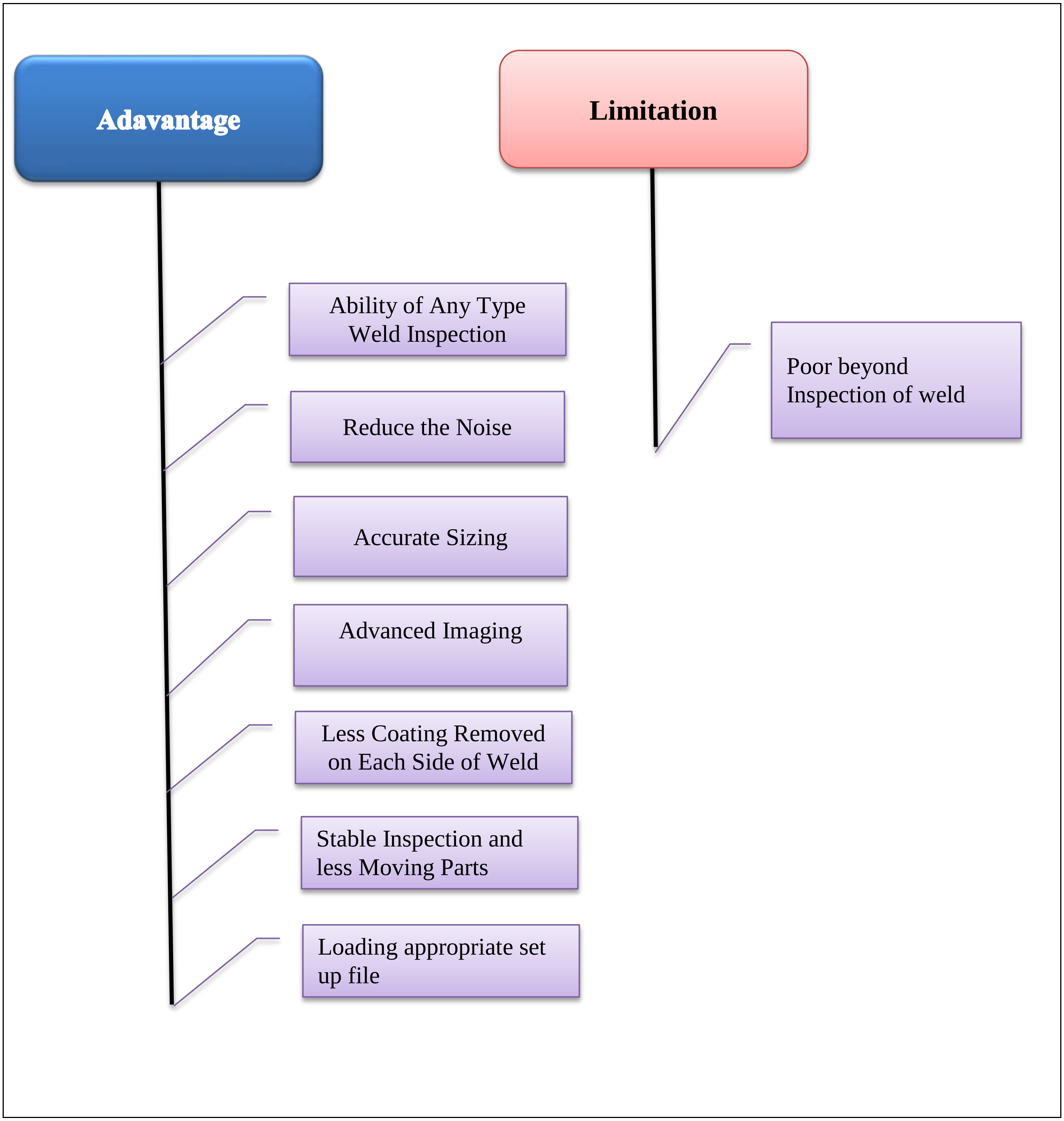


Figure 6.6.3 Consideration of Phased Array Technology

5.6.4. Ultrasonic Doppler Technique

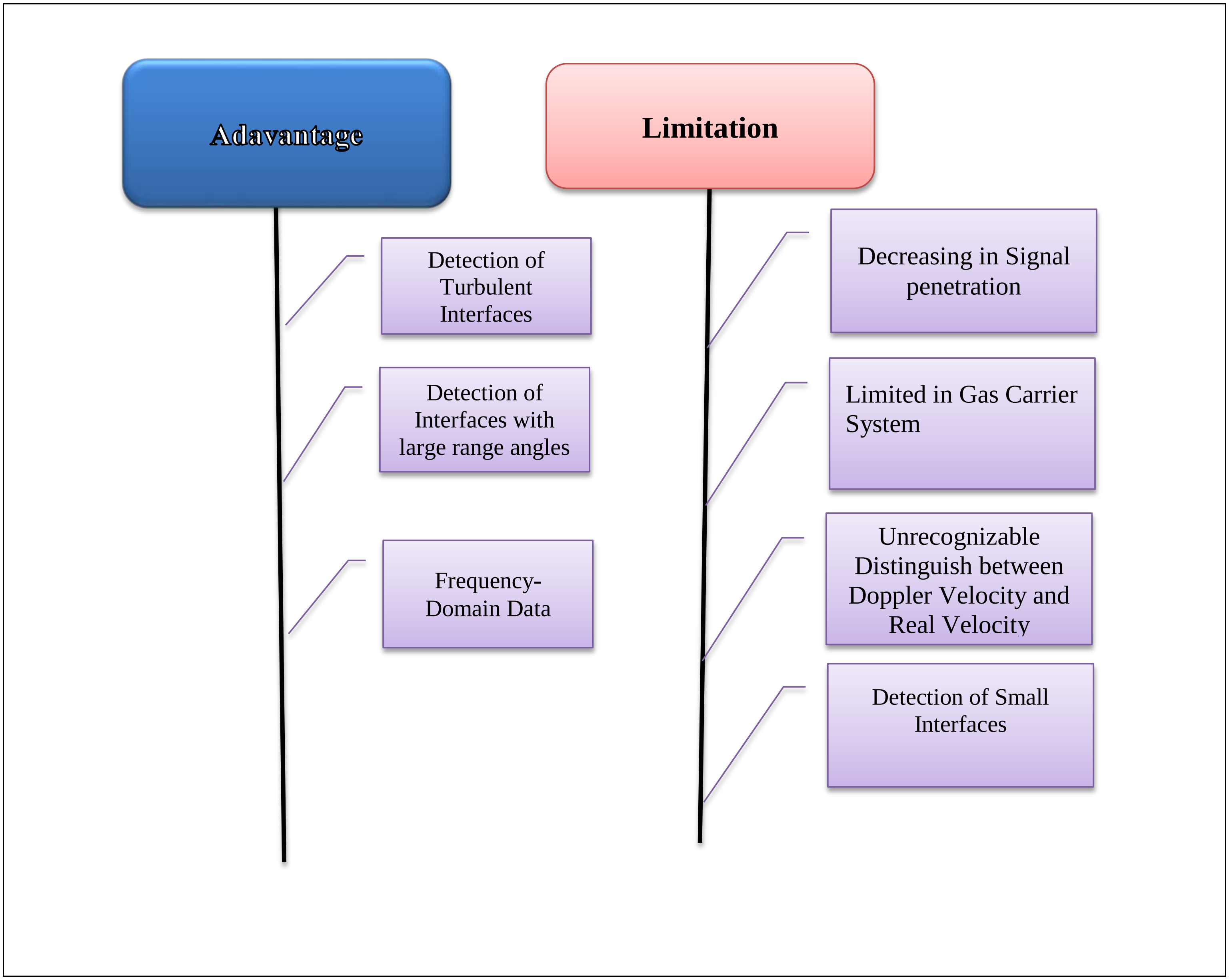


Figure 6.6.4 Consideration of Ultrasonic Doppler Technique

7. Conclusion

The recent realizations of the UT system for inspection of metal loss, flow measurement and accumulation and plugging of an offshore pipeline are presented.

A review of basic ultrasonic detection methods, outcome illustrations and interpretation methods of the obtained results are accomplished.

Various ultrasonic transducers used as origin of ultrasounds are defined and different technique modes of sensor systems were evaluated. The applicability of ultrasonic transducers for localization and detection of pipeline flaws and flow measurements are identified and rational evaluations are carried out.

The industrial necessities for initiative solutions have been widely discussed.

For detection of pipeline small defects the phased-Array system is considered to be the most preferred inspection technique, but still it has limitations which require subsequent developments.

Ultrasonic Doppler flowmeters is the most recommended method for measuring different compositions of flow interfaces.

The applicability and efficiency of existing techniques depend on absence of flow turbulence and minimum attenuation.

The stimulants for a non-invasive methodology such as UT include affordably, its low risk and the present limited accessibility of offshore pipelines. More effective and accurate inspection methods are extremely required. Further recovery potentials are mentioned in the concluding part, section 8.2.

8. Future Ultrasonic Inspection Technologies

8.1 Industry Innovational Solution for UT

The Ultrasonic Tomography system is still one of the major technologies to deal with inspection challenges. The performance and efficiency of inspection methods depend on the penetration rate, frequency, attenuation rate (time-based, low-energy diffracted signals), temperature and the interfaces situation and quality of the imaging method. Today, novel techniques for probes, sensors, electronic devices and tomographic reconstruction are greatly required. Ultrasonic methods allow low inspection risk and reliable measurements.

Some qualifications that are demanded for ultrasonic testing are as following (ABLE’s Flowmeter):

- Tough submersible design for use in harsh industrial environments
- Multi-path versions for increasing precision and flexible in respect of distortions of flow profile
- Ideal for natural and process gas applications
- Available in wall, rack and barrier settings
- Resistant of most wet gas conditions
- Protected from the most pressure reducing noise of valve
- Friend-use diagnostic software
- Optional tough stainless-steel transducer enclosure provides stable and direct burial installations
- Portable meters can be employed for flow measurements and to prove existing meters
- Suitable for different pipe sizes
- Low- weight design, fast and simple installation
- Easy operation
- Good performance in bends, valves and flanges

These points may increase the Ultrasonic Testing applicability and also may make it more expensive.

8.2 Interdisciplinary Adaptation of Ultrasonic Technology

These days, research in the biomedical industry is highly admirable. In the attempt to creation of coalition between technologies applied in other industries, an interdisciplinary research is required. Techniques of visualizing fetuses, of breaking up tissue and accelerating the effects of drugs therapies have been found to be an interesting comparison with pipeline inspections The similarity is noticeable, despite large difference in size and context.

Metamaterial provides considerable superiorities over the conventional ultrasound technology. This new material has been introduced by (Yakovlev et al., 2013) and it produces images by transforming ultrasound waves into optical signals. Polypyrrole is a kind of polymer that along with the embedded gold nano-rods makes up this metamaterial (Yakovlev et al., 2013).

In Figure 8.2.1., the red arrow to the left is displayed an optical signal. This signal is sent to the metamaterial and encounters to the material as ultrasound waves before travelling through the material. The outcome that is obtained from a converted optical signal results in higher resolution image.

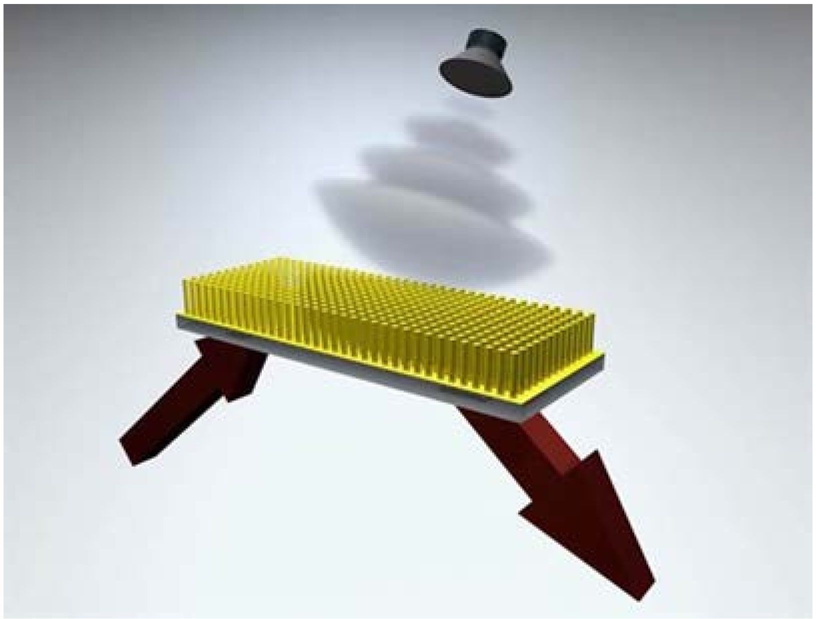


Figure 8.2.1 Metamaterial Usage in Ultrasonic Technology

However, bandwidth and sensitivity are two limitations that can largely effect sonogram images, however the optical processing of ultrasound improves these problems. A high bandwidth provides the possibility to inspect the distant changes of the acoustic waves with a high accuracy. This image translation leads to higher sensitivity and allows you to monitor the body tissue in higher details.

This advancement enables production of a signal in a frequency range between 0 to150 MHz without sensitivity reduction. The existing technology usually declines in a frequency range around 50MHz (Yakovlev et al., 2013).

8.3 Halfwave's Discovery

The company Halfwave offers a technology and deliver system which is developed sufficiency compared to other existing inspection technologies such as conventional ultrasound and magnetic flux measurements. Acoustic Resonance Technology (ART) is an invention broad-band/medium frequency inspection, based on known physical principles (Ref: Halfwave Descipline).

Halfwave has made an improvement in the terms of transducers, electronics and algorithms. A combination of these three sections is the basic principles of ART in industrial demands. The technology associated with in-line inspection (ILI) tooling has been constructed based on inspection delivery systems. ART is aiming to improve non-destructive testing and assessment of important assets in the oil & gas industry (Ref: Halfwave Descipline).

A transducer generates a broad-band acoustic signal towards the metal structure. The signal that propagates through the structure stimulates half-wave resonances. A specific signal which is diagnosed by the receiving transducer is transmitted by the response of the structure. This response signal is a component of the frequency analysis that results in resonance frequencies. By resonance frequencies the base resonance frequency, and finally the structure's thickness are determined (Ref: Halfwave).

One of Halfwave's products is ART scan (see Figure 8.2.2) that offers great inspection implementation in bends. It is a solution for pipeline internal inspections as well as being capable to measure the wall loss directly (Ref: Halfwave).

Figure 8.3.1 ART-Scan Pipeline Inspection Solution

(Ref:Halfwave)

In addition, it is capable to inspect multi-diameter pipelines and decrease the leak incidents and develop the technical safety of gas pipelines.

Halfwave’s ART technology is an innovation related to the three following tasks (Ref: Halfwave):

- Accuracy: Halfwave’s ART offers precise imaging such as wall thickness mapping in gas pipelines with wall thickness over 100 mm (Ref: Halfwave Descipline)
- Penetration: ART doesn’t need to remove the thick subsea coating and it can penetrate it easily
- Flexibility: appropriate inspection for un-piggable applications

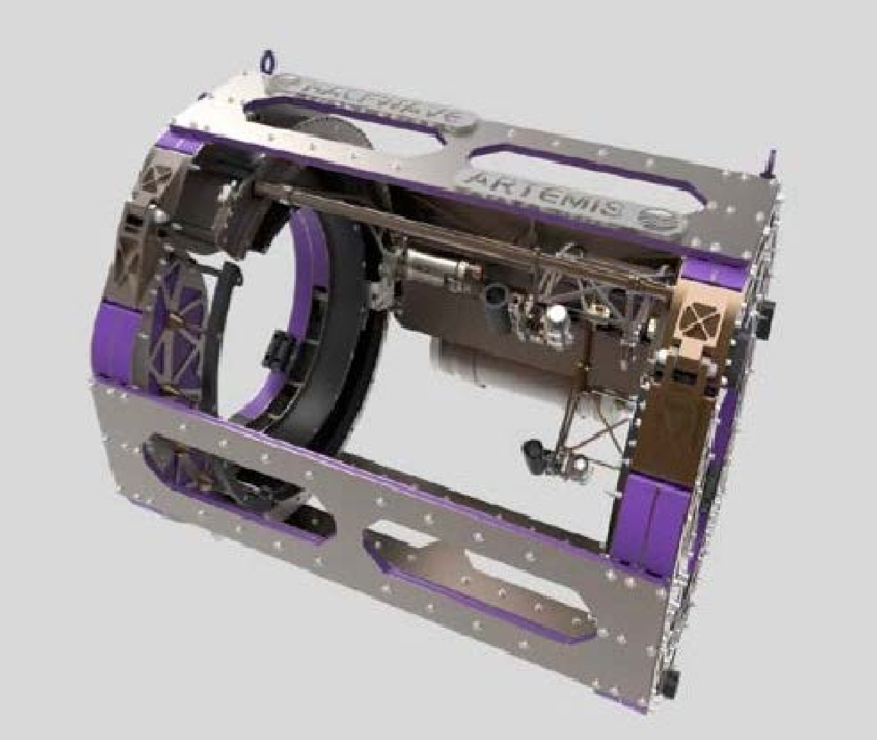


Figure 8.3.2 ARTEMIS (Acoustic Resonance Technology Measurement External Inspection Subsea)

(Ref: Halfwave)

ARTEMIS is an external inspection tools which is displayed in Figure 8.2.3. It meets the applications of both rigid and flexible inspection of flow lines, it has 360 degree coverage, and it has the possibility of lateral movements along the pipeline and penetrates through the pipeline coating (Ref: Halfwave).

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