TOMOGRAPHIC INSTRUMENTATION SYSTEM BASED ON ULTRASONIC SENSOR FOR MONITORING IRREGULARITIES IN PIPE

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I dedicated this thesis to my beloved family especially my father Ramli Bin Mat Taib and my mother Mastura Binti Kusaini, my lecturers and friends who are always stand by my side in accomplishing this thesis.

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ABSTRACT

The formation of irregularities inside pipes is a common phenomenon that occurs in the chemical industry. The presence of irregularities on the surface of the internal pipe wall can lead to corrosion which eventually reduces its own integrity for operation. Many methods have been developed for the prevention and detection of this problem. An ultrasonic is one of the non-destructive methods used in the industrial sector. An ultrasonic instrumentation system has been developed in this project to detect the presence of internal irregularities in a pipe. The variations of ultrasonic signals were observed in the experiment when it passed through different conditions of the internal pipe surfaces. An ultrasonic Sensor EFC16T/R-2 with a frequency of 40 kHz was mounted outside the test pipe using a circle ring sensoring unit. The results showed that there were changes of output voltage when there were irregularities detected in the ultrasonic path. The output voltage was low in the range of 2.1333V to 3.1334V when there were no irregularities detected inside the steel pipe. The increase in output voltage from 5.4677V to 8.8667V indicated that the absorption of ultrasonic signals by irregularities had occurred. The collected data were processed using Matlab software to reconstruct the images inside the pipe. The reconstructed images showed the irregularities detected inside the pipe that resembled the actual conditions of the pipe. However, several images showed a slight inaccuracy of irregularities position in the test pipe compared to the actual condition of the pipe. This was due to the instability of ultrasonic signals, which could be easily affected by environmental factors and the presence of noise during the experiment. Nonetheless, it is believed that the developed ultrasonic tomography was able to monitor any irregularities present inside a pipe.

ABSTRAK

Pembentukan ketaksekataan di dalam paip adalah fenomena yang biasa berlaku dalam industri kimia. Kehadiran ketaksekataan pada permukaan dinding dalaman paip boleh mengakibatkan pengaratan yang akhirnya akan mengurangkan keutuhannya untuk beroperasi. Banyak kaedah telah dibangunkan untuk pencegahan dan pengesanan masalah ini. Ultrasonik adalah salah satu kaedah tanpa-musnah yang digunakan dalam sektor industri. Sistem instrumentasi ultrasonik telah dibangunkan dalam projek ini untuk mengesan kehadiran ketaksekataan dalaman paip. Kepelbagaian isyarat ultrasonik telah diperhatikan dalam ujikaji ini apabila melalui keadaan yang berbeza di permukaan dalaman paip. Penderia ultrasonik EFC16T/R-2 dengan frekuensi 40 kHz telah dipasang di luar paip yang diuji dengan menggunakan unit penderiaan gelang bulat. Keputusan menunjukkan terdapat perubahan pada voltan keluaran apabila ketaksekataan dikesan pada laluan ultrasonik. Voltan keluaran adalah rendah dalam julat antara 2.1333V sehingga 3.1334V apabila tiada ketaksekataan dikesan di dalam paip keluli. Kenaikan dalam voltan keluaran daripada 5.4677V sehingga 8.8667V menunjukkan penyerapan isyarat ultrasonik oleh ketaksekataan telah berlaku. Data terkumpul telah diproses menggunakan perisian Matlab untuk membina-semula bayangan di dalam paip. Bayangan yang dibina-semula menunjukkan ketaksekataan dikesan pada dalaman paip dan ini menyerupai keadaan sebenar paip. Walaubagaimanapun, beberapa bayangan menunjukkan sedikit ketidakjituaan kedudukan ketaksekataan dalam paip yang diuji berbanding dengan keadaan paip sebenar. Ini disebabkan ketidakstabilan isyarat ultrasonik yang terjejas dengan mudah oleh faktor persekitaran dan kehadiran hingar semasa ujikaji. Namun begitu, ultrasonik tomografi yang dibangunkan mampu mengawas sebarang ketaksekataan yang hadir dalam paip.

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LIST OF ABBREVIATIONS

ECT	-	Electrical Capacitance Tomography
EIT	-	Electrical Impedance Tomography
NPP	-	Nuclear power plant
RR test	-	Round Robin test
QL	-	Q-switched continuous wave laser
DAS	-	Data acquisition system
NMR	-	Nuclear magnetic resonance
CFRP	-	Carbon fiber reinforced plastic
PWAS	-	Piezoelectric Wafer Active Sensors
GRP	-	Glass-fibre-reinforced polymer
SVM	-	Support Vector Machine Multi-classifier

LIST OF SYMBOLS

c	-	Velocity of Ultrasonic Wave in the Medium
cm	-	Centimeter
2D	-	Two Dimensional
kg	-	Kilogram
kHz	-	Kilohertz
L	-	Length
m	-	Meter
V	-	Voltage
Z	-	Acoustic Impedance
°C	-	Degree Celsius
CO_2	-	Carbon Dioxide
H_2S	-	Hydrogen Sulphide
Fe	-	Ferum
FeO	-	Ferum Oxide
α	-	Attenuation coefficient
D	-	Transmission coefficient
P_o	-	Initial pressure
P_x	-	Pressure at distance of x
P	-	Density of the material
R	-	Reflection coefficient
A_o	-	The incident amplitude

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Tomography is defined as a process of imaging by sectioning interior solid materials from the outside using waves of energy without affecting the object. Process tomography can give real-time cross-sectional images inside the materials (Grangeat, 2013; Martin.J *et al*., 2001). In the process of tomography, a 2D or 3D image of some physical quantity inside the object can be obtained using external sensors to detect signals from the boundaries of the object (Dickin *et al*., 1992; Schlaberg *et al*., 1997)

This process also involves getting measurements and data in order to investigate what is going on inside the particular material, such as a vessel or pipeline. The measurements are usually based on temperature, pressure, power level, component geometry and others (Dickin *et al*., 1992).

Process tomography consists of three basic elements. The elements are sensors, a sensor electronic circuit and an image reconstruction system. The most important element is the sensor because how the sensor interrogates the process and information obtained from the process will affect the accuracy of the whole system (Dickin *et al*., 1992).

There are several tomography sensors commonly used in the industry. Some examples are the ionising radiation which is x-ray and γ-ray, nuclear magnetic resonance (NMR), acoustic tomography and microwave. These tomography sensors have different applications and techniques, depending on the subject that is going to be investigated (Ismail *et al*., 2005). Figure 1.1 shows the basic schematic diagram of tomography.

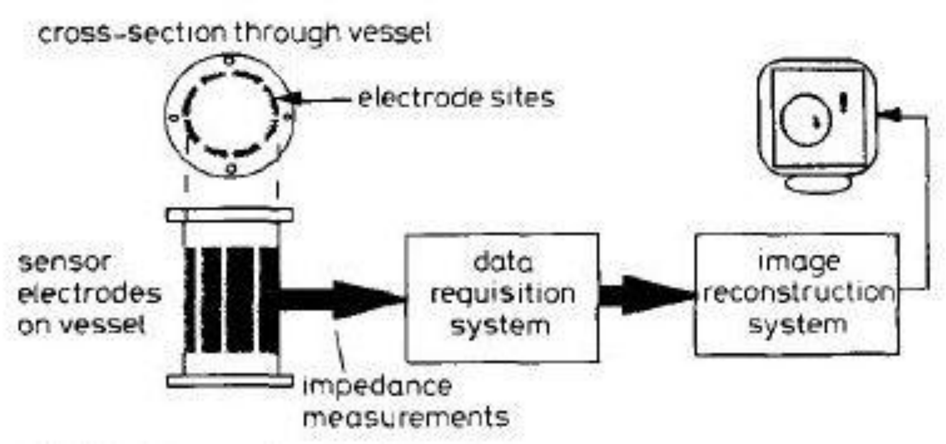


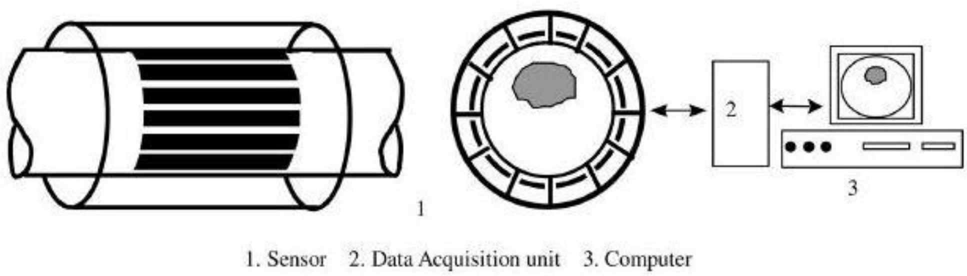
Figure 1.1: Schematic diagram of tomography (Dickin *et al.*, 1999)

The ultrasonic signal is transmitted from the transmitter and propagated along the tested material. The signal will be received by the receiver and sent to the Data Acquisition System (DAS) to be analysed. The final result will be in image form after being processed in an image reconstruction system. The ultrasonic sensors can be divided into transmission-mode, reflection-mode and emission-mode. These modes are based on the change of physical properties of the transmitted signals. There will be changes of output voltage when there are any obstructions in the ultrasonic path length, which indicates that the absorption of ultrasonic signals has occurred (Abdul Rahim, 2007).

1.2 Overview On Tomography And Its Application

Tomography has become one of the most important techniques and has been applied in various kinds of fields such as medical, engineering, biotechnology and others.

Electrical Capacitance Tomography (ECT) has been widely applied in the chemical and petroleum industries. This method has been applied to obtain real time visualizations of the industry's processes and void fraction measurements of the two-phase flow. The system consists of a flow measurement technique for the gas-oil two phase flows using an ECT system incorporating a differential pressure measuring device (Huang *et al*., 2005). Figure 1.2 shows the schematic diagram of the system.



. **Figure 1.2**: Schematic diagram of ECT (Huang *et al.*, 2005)

The results showed that ECT is an attractive and effective technique in measuring the flow of the gas-oil in two phases. This technique has high-speed capabilities, reliability, simplicity and non-invasion properties (Huang *et al*., 2005).

Electrical Impedance Tomography (EIT) is used to measure process impedance, phase and reactance. Impedance is to determine real and imaginary parts, which gives sets of data in order to understand any complex material and how the data is distributed in the process. For example, in the process of indirect coal liquefaction where a reactive gas is bubbled through a slurry laden with catalysts, a spatial non-uniform gas distribution can occur within the reactor. This situation can reduce the process efficiency by inducing large-scale, buoyancy-driven re-circulating flows. For this situation, techniques that are capable in measuring the distribution of each phase in multiphase flows must be applied to improve the control of such processes (Georgea *et al*., 2000).

The technique can be used for validating computational models of multiphase flows. EIT is applied in a process where it can provide spatially resolved information on dispersed multiphase flows. EIT methods are relatively mature and able to measure spatial phase distributions accurately (Georgea *et al*., 2000).

Seismographic Tomography is used to interpret data and generate three dimensional or two dimensional images of the internal parts of the Earth. There are two energy sources for seismic tomography. One of them is from earthquakes. When earthquakes happen, it will generate waves that can be picked up by a receiver on the surface of the Earth. Geologists will be able to create images of the layers where the waves pass through (Rawlinson *et al*., 2010).

Seismic Tomography will show the actual shapes of rocks in the Earth because the waves' movements are different when it passes through different rocks. Other sources are from the waves generated by geologists and its corresponding reflections. This method can be applied to observe the desired area. The wave energy produced can be tracked by its own reflection (Nolet, 1987).

Transmission and Emission Tomography is commonly used in the medical field as a technique of obtaining the structure of the body as well as physiological functions. However, this method has been accepted in other industries and acts as a powerful tool for non-destructive testing. An emission tomography system has been applied in nuclear power plants. Experiments have been carried out to stimulate the scanning of irradiated nuclear fuel (Hutchinson *et al*., 1987).

Optical Tomography is one of the methods commonly used in industries. The optical method has become a powerful tool for verification of materials in process industry. In the micro electric field, great support has been given to the online measurement of doping profiles of large scale productions so that the overall equipment effectiveness can be increased (Zeni *et al.*, 2000).

In this situation, a new technique has been introduced based on optical tomography. Optical tomography is able to reconstruct the doping profiles of semiconductor wafers, which begins with the reflected intensity measurement taken at infrared wavelengths. The measurement of material characteristics is important to improve the reliability of process simulators (Zeni *et al.,* 2000)

1.3 Overview of Ultrasonic Wave

Ultrasonic wave is a description of waves that transport mechanical energy through vibrations at the frequency of 20 kHz or more (Leighton, 2007). The frequency of ultrasonic waves is above the range of a normal person's hearing (Makar *et al.*, 1999). The frequency commonly used for testing is about 20 kHz to 25MHz (Bindal, 1999).

Ultrasonic waves are also known as stress waves and only exist in mass media. It needs a medium to propagate. The signal transmits the energy to another medium by direct contact between them. From this characteristic, ultrasonic sound is different from light and radiation waves which can propagate through vacuum or without medium (Ensminger, 2009). Figure 1.3 shows the location of ultrasonic sound in the mechanical wave spectrum.

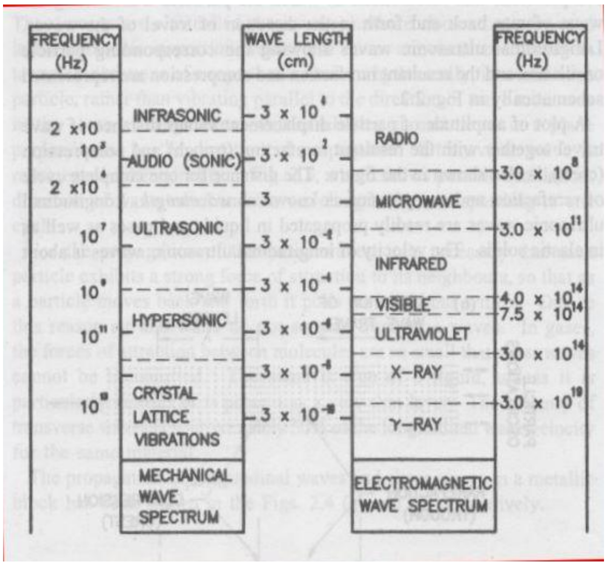


Figure 1.3: Mechanical and Electromagnetic wave spectrum (Ensminger, 2009).

1.4 Ultrasonic Wave Characterization

Generally, ultrasonic waves can propagate in numerous ways. For example, longitudinal waves, transverse waves, lamb or plates waves and head waves. The longitudinal and transverse waves are the most important and widely applied in ultrasonic applications. A longitudinal wave travels through mediums by alternate compression and rarefaction in which the transfer of waves vibrates the nearest particles moving in the direction of the travel wave (Bindal, 1999).

The distance for one complete cycle of rarefaction and compression is called a wavelength. The longitudinal wave can propagate in liquid and gas forms. The transverse waves vibrate up and down in a plane that is perpendicular to the direction of wave. It is necessary for the particles to have strong attraction forces with the adjacent particles so that it can move back and pull its neighbour with it (Bindal, 1999). Figure 1.4 shows the propagation of longitudinal and transverse waves.

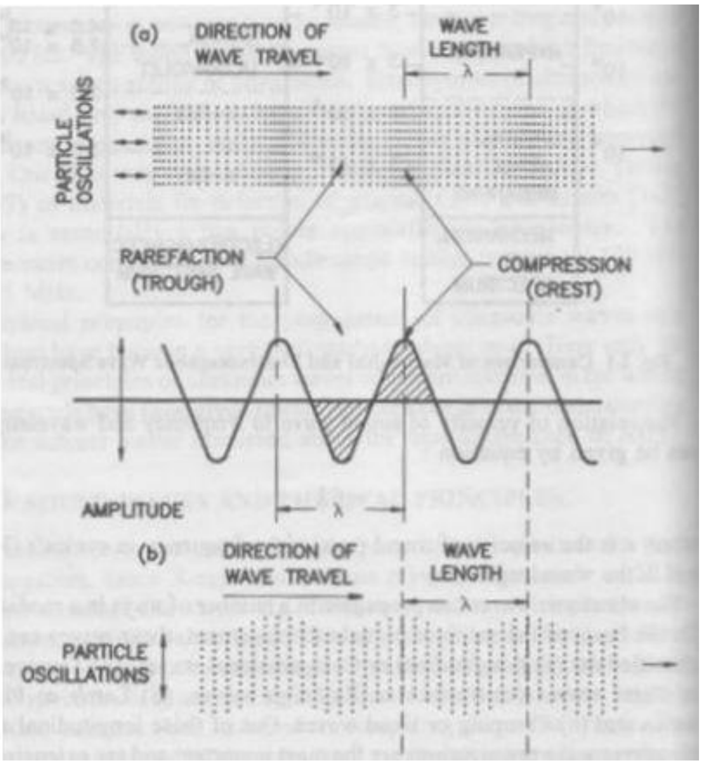


Figure 1.4: Propagation of longitudinal and transverse wave (Bindal, 1999).

1.4.1 Reflection and Refraction

When an ultrasonic wave is transmitted to two different mediums at a normal incident, it will be transmitted as a longitudinal beam from the first medium to the second medium. Since these mediums are different in its elastic properties, the total energy is not transferred from the first medium and the second medium (Beck *et al*., 1995). When the sound wave strikes the interface between two different media, it is partially reflected while the other part passes through the interface. The wave will go through the second medium until it either gets absorbed or reflected back when it hits the back of the second medium (Bindal, 1999).

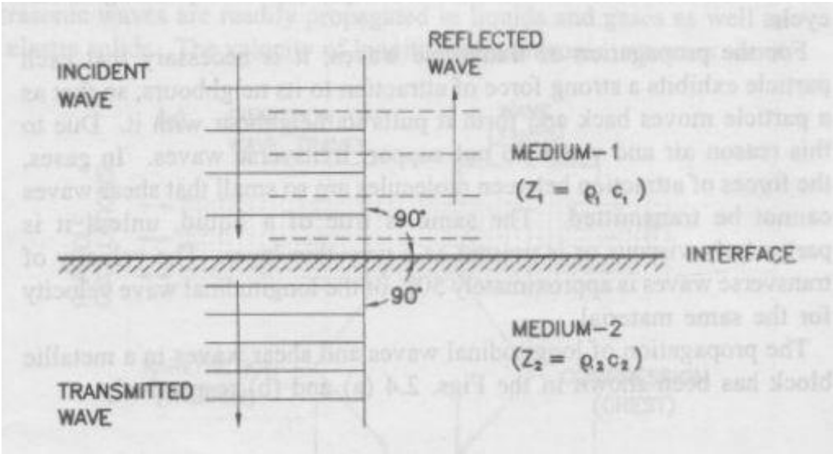


Figure 1.5: Reflection of sound wave (Bindal, 1999).

The law of reflection and refraction of ultrasonic waves are similar to the law of light. When an ultrasonic wave strikes at an angle A, a change in a medium with different acoustic impedance, reflection and refraction of sound energy happens with a change of mode of vibration (Beck *et al*., 1995). Acoustic impedance is defined as a characteristic of mediums (Bindal, 1999). Figure 1.6 shows the refraction of a sound wave.

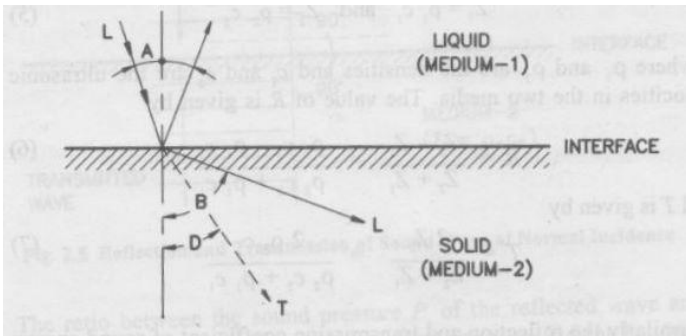


Figure 1.6: Refraction of sound wave (Bindal, 1999).

When an ultrasonic wave passes through the interface at angle A, the change of propagation direction is based on Snell's Law, shown in the formula below.

$$\frac{Sin\ A}{Sin\ B} = \frac{C1}{C2} \tag{1.1}$$

Where A is the angle of incidence meanwhile B is the refraction angle. C1 and C2 are the velocity of waves when it passes through two different mediums (Bindal, 1999).

1.4.2 Diffraction

When the direction of sound wave changes as it passes through an opening along its path, it will cause diffraction (Sen, 1990; Peter *et al*., 2010). Ultrasonic waves do not require changes of medium to diffract. We can observe the phenomenon of diffraction when we hear people talking to us from another room (Raymond *et al*., 2000). It shows that the sound waves are diffracted through the opening door (Berg, 1995). Figure 1.7 shows the simple diffraction of sound.

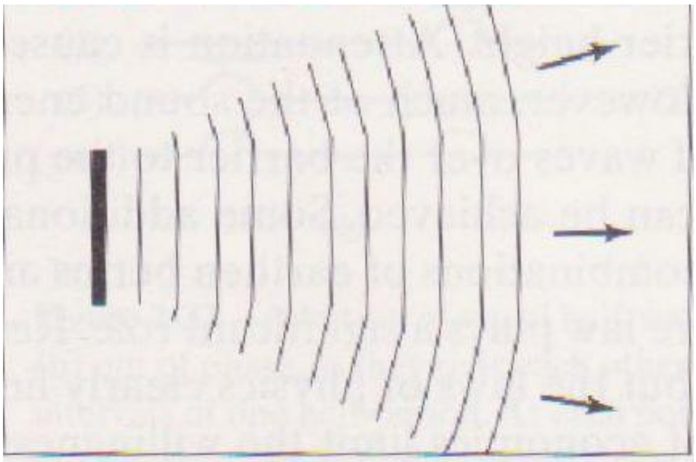


Figure 1.7: Diffraction of sound wave (Berg, 1995)

The concept of diffraction states that the larger the ratio of wavelength to the size of opening or obstacles, the greater the diffraction effect produced. Figure 1.8 shows that the sound wave is propagated towards the reflecting wall and the small aperture in the wall. The dimension of the aperture in the wall is smaller than the wavelength. When the wave hits the wall, most of the sound wave is reflected by the wall and only a small portion is transmitted through the small aperture. It is clear that the wave passing through the aperture is spreading to all directions. The intensity of the diffracted wave is much lower because there is only a small amount of energy transmitted by the aperture (Olson, 1967).

Figure 1.8: Diffraction through small aperture (Olson, 1967)

Figure 1.9 shows the diffraction effects when an aperture has a larger dimension compared to the wavelength. When the wave passes through the aperture, it will be transmitted through it without any loss of intensity. So, the diffracted wave will be seen as identical to the shape of the aperture (Olson, 1967).

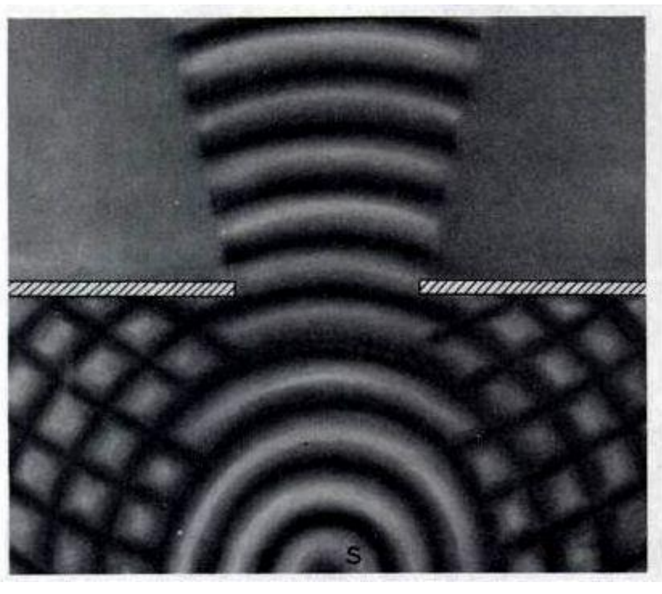


Figure 1.9: Diffraction through large aperture (Olson, 1967)

The sound wave that passes though small obstacles is illustrated in Figure 1.10. The sound wave bends around the obstacle and the shadow produced is considered negligible. The small obstacle does not give any effects to the wave. due to the size of obstacle is smaller than the wavelength, the diffracted wave is considered negligible (Olson, 1967).

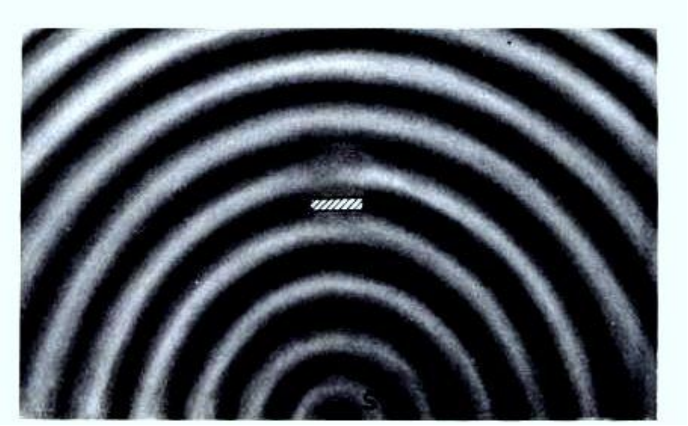


Figure 1.10: Diffraction through the small obstacle (Olson, 1967)

When a sound wave is diffracted through a big obstacle which has a larger dimension than the wavelength, the sound intensity produced at the back of the obstacle is small. The obstacle will produce an almost perfect sound shadow. Since the size of obstacle is larger, most of the wave is reflected to the surroundings (Olson, 1967). Figure 1.11 shows this situation.

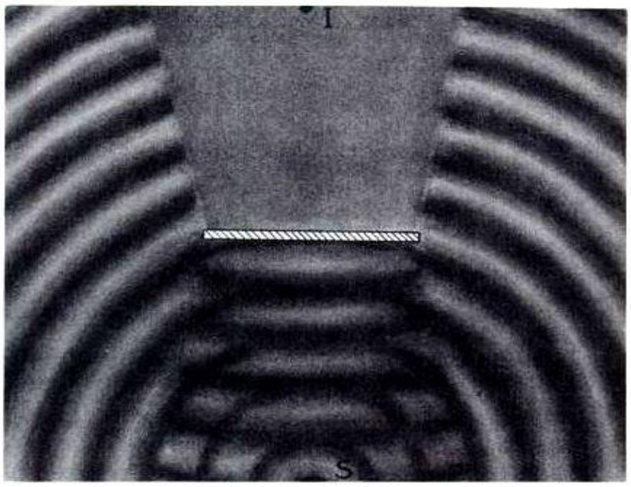


Figure 1.11: Diffraction through the big obstacle (Olson, 1967)

1.4.3 Absorption

The absorption of sound occurs when the sound energy is diminished as the wave passes through a medium or strikes a surface. The absorption of sound mechanism is usually the conversion of sound wave into heat. When the sound is absorbed into a porous substance, the sound is converted into heat energy by transmission. The wave sound will be transmitted through a narrow passage. The dimension and length of passage for sound-absorbing materials are designed so that it can maximise the absorption of sound. Figure 1.12 shows the absorption of sound (Olson, 1967).

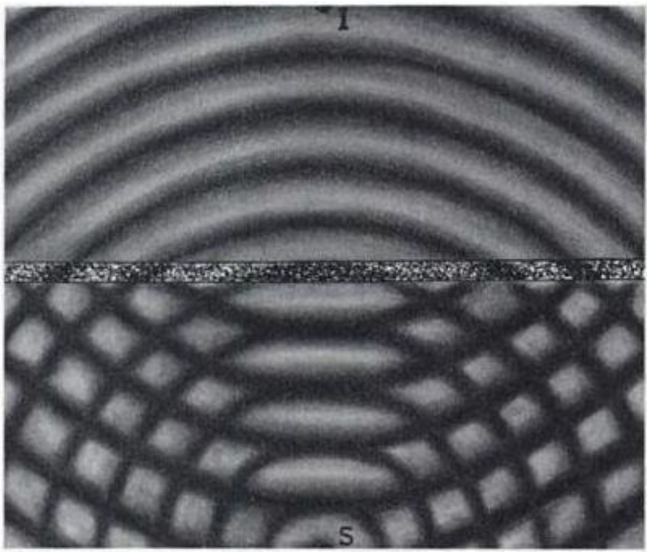


Figure 1.12: Absorption of the sound (Olson, 1967)

The mechanisms of reflection, absorption and transmission will take place in the walls or other boundaries. Figure 1.12 shows that parts of the wave is reflected, while parts of them are absorbed and transmitted by the walls (Olson, 1967). Equation 1.2 is related to absorption of sound by:

$$\mathbf{P_x = P_o}\, e^{-\alpha x} \tag{1.2}$$

Where Po is the initial pressure at starting point, Px is pressure at distance of x from Po, and parameter α is the 'absorption coefficient' for the medium where the wave travels. Ultrasonic waves are generated based on the conversion of non-physical energy (pressure) to mechanical energy (voltage). Pressure is a unit for ultrasonic waves and it is obtained by measuring the decrease of pressure when a wave travels through different materials (Sen, 1990). In the experiment, pressure of the ultrasonic waves is converted to terms of voltage using an oscilloscope. Voltage values obtained from the experiment are used to generate the final image of the insides of the pipe.

1.5 General Overview Properties of Clay

Clay is formed from a natural composition of fine-grained minerals. It can exist in plastic form when it has appropriate water content and can be hardened when fired or dried. It is generally accepted that crystals make up the major content of clay (Theng, 2012). Very fine clay such as smectite is resistant to water because at high densities, compacted clay will exert water suction (Bergaya *et al*., 2011).

Clay materials have special properties, including cation exchange properties, plastic behaviour when wet, catalytic abilities and low permeability. It is because clay exists in the form of small size particles and has a unique structure (Theng, 2012). The conductivity and strain/stress properties of clay is different as compared to soil sand due to its particle size and the electric charges that makes them interact and hydrate with each other (Bergaya *et al*., 2011).

Clay mineral has been used widely in industries, such as coating on paper to produce whiteness, in the tyre industry in order to prolong the life of rubber, purification of oils and many other industrial processes. Montmorillonite clay is commonly used as clay barriers for nuclear and chemical wastes. It is due to its special properties which are cation-exchange capabilities, long term structural stability, and low permeability (Theng, 2012).

1.6 Problem Statement

Most pipelines will experience deterioration in terms of integrity due to natural causes, operating conditions and maintenance of the pipeline. This is due to the irregularities present inside the pipe. The existence of irregularities inside the pipe can contribute to pitting problems. There are several causes that may lead to the formation of irregularities such as spillages of soldering flux inside the pipe during welding processes. Improper joints and bends of pipes can also be the cause of irregularities (Cantor, 2009).

Irregularities also can be formed due to high water velocities flowing inside pipes which basically will scour the pipes' walls. This phenomenon will lead to the formation of localised corrosion inside the pipe (Hayes, 2011). The corrosion can affect the original physical properties of the pipeline. Corrosion at the internal surface of pipelines can reduce the material's functions and the pipe's lifespan (Nuhi *et al.*, 2011).

Irregularities such as dents, scratches and bumps inside pipes will force fluids to flow to other smooth surfaces and the fluid's velocity will be different from its original velocity. This will cause a turbulence flow inside the pipe. The turbulence flow of the fluid will affect the delivery rate of piping system and reduce the production rate (Spellman, 2013).

Many ways have been taken to overcome this problem. For example, an internal inspection device named the smart pipe inspection gauge (PIG) was invented. However, the smart PIG is not suitable for all pipelines. Since most of the gas pipeline consists of sharp bends, reduced port valves and loops, these conditions will cause problems for the smart PIG's operational inspection. The smart PIG tends to get stuck in the middle of the pipe during operation due to this problem. When the smart PIG gets stuck, the whole operation must be shut-down and it will cost more money for its cleaning process. (Meisner, 2006).

Ultrasonic is commonly used in the oil and gas industry for monitoring irregularities inside the pipe. This technique is able to locate and visualise the presence of irregularities inside the pipe (Mudali, 2006). Ultrasonic tomography is a non-invasive technique. Non-invasive technique means that sensors are mounted outside the pipe to be tested without making any changes to it, such as drilling a hole. Ultrasonic tomography also does not interfere with the processes inside the pipe during operation (Abdul Wahab, 2015).

1.7 Objective

The objectives of this research are:

1. To develop a tomographic instrumentation system for monitoring irregularities based on ultrasonic sensors.
2. To detect the presence of irregularities in pipes using ultrasonic tomography and to display the image of irregularities in two-dimension images.
3. To detect the location of irregularities inside pipes based on the two-dimension images obtained from the processed data from the Matlab simulation

1.8 Scope of study

1. Study on the general concept and theory of tomography and its mechanism.
2. Study on the properties and characteristics of ultrasonic wave and how it travels from its sources and also its interactions with different materials.
3. Obtain experimental data based on the transmission mode of ultrasonic tomography.

4. Obtain two-dimension images of corrosion inside different conditions, such as clean and corroded pipes using the Matlab software.

1.9 Limitation of study

1. The system is limited to detect the presence of irregularities inside pipes. It is unable to measure the type and degree of irregularities detected.
2. The images generated in the final result were 2-Dimensional.
3. The ultrasonic sensors are not able to detect very small irregularities.

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