DEVELOPMENT OF ULTRASONIC TOMOGRAPHIC INSTRUMENTATION SYSTEM FOR MONITORING FLAWS ON PIPELINE

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This thesis is especially dedicated to my beloved parents, Nordin Harun and Meriam Ibrahim, sisters and dearest friends. May Allah bless all of you forever.

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ABSTRACT

Online inspection and in situ monitoring for natural gas transmission and distribution pipeline is significant to prevent any fatal incident and to maintain pipe integrity. Most inspection technique conducted in industry is for the localized flaws detection. It is important to have an inspection system that is capable of producing an overall image of pipe profile (circumferentially) which can show the actual location of the flaws. Therefore, an ultrasonic tomographic instrumentation system was designed and fabricated for this study to monitor the existence of flaws circumferentially on pipeline. It consists of an ultrasonic sensing system, a data acquisition system and an image reconstruction system (software development). There were twenty-eight ultrasonic sensors arranged on a sensing ring that surrounded a carbon steel pipe NPS 8 (219 mm external diameter). The sensors were contactless to the pipe at a distance of 50 mm. Several testings were conducted to identify the ultrasonic beam pattern, the uniformity of ultrasonic beam intensity and the image grid covered by each sensor. A calibration test on distance measurement was conducted based on 40 mm to 60 mm range of distance, and the result showed ± 0.3 mm maximum error with the average accuracy of 99.82%. Three experiments on flaws detection around the pipe were carried out, which were the external flaws, internal flaws and a combination of external and internal flaws. The depth of flaws was ranging from 0.4 mm to 3.3 mm. From the output data, a tomogram image of the circumference pipe profile with flaws existence was reconstructed using linear back projection algorithm and direct method. The computer programming on image reconstruction was performed using MATLAB software. In brief, the developed ultrasonic tomography system was capable in detecting the flaws on pipeline, and visualizing the actual location of the flaws.

ABSTRAK

Pemeriksaan dalam talian dan pemantauan secara terus terhadap talian paip penghantaran dan pengagihan gas asli adalah penting untuk mengelakkan sebarang kejadian yang boleh membawa maut dan mengekalkan integriti paip. Kebanyakan teknik pemeriksaan yang dijalankan dalam industri adalah bagi mengesan kecacatan setempat. Adalah penting untuk mempunyai sistem pemeriksaan yang mampu menghasilkan imej keseluruhan profil paip (lilitan) yang menunjukkan lokasi sebenar kecacatan yang wujud. Oleh itu, sistem instrumentasi ultrasonik tomografi telah direka bentuk dan dibina untuk mengawasi kehadiran sebarang kecacatan pada lilitan paip. Ini terdiri daripada sistem penderiaan ultrasonik, sistem perolehan data dan sistem pembinaan semula imej (pembangunan perisian). Terdapat dua puluh lapan penderia ultrasonik disusun pada gegelung penderia di sekeliling paip karbon keluli NPS 8 (219 mm diameter luar). Penderia ultrasonik tersebut tidak bersentuhan dengan paip pada jarak 50 mm. Beberapa ujikaji telah dilakukan untuk mengenal pasti corak alur ultrasonik, keseragaman keamatan alur ultrasonik dan grid imej yang diamati oleh setiap penderia. Ujian penentukuran jarak telah dijalankan berdasarkan julat jarak 40 mm hingga 60 mm, dan hasilnya menunjukkan ralat maksima ± 0.3 mm dengan kejituan purata 99.82%. Tiga ujikaji pengesanan kecacatan di sekitar paip telah dijalankan, yang melibatkan kecacatan luaran, kecacatan dalaman, dan gabungan kecacatan luaran dan dalaman. Kedalaman kecacatan adalah antara julat 0.4 mm hingga 3.3 mm. Daripada keputusan data, imej tomogram bagi profil lilitan paip dengan kecacatan telah dibina semula menggunakan algoritma unjuran belakang lurus dan kaedah langsung. Program komputer bagi membina semula imej ini dilaksanakan menggunakan perisian MATLAB. Secara ringkas, sistem tomografi ultrasonik yang dibangunkan ini mampu mengesan kecacatan pada talian paip, dan memberi gambaran lokasi sebenar kecacatan.

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LIST OF ABBREVIATIONS

A	-	Amplitude
A1	-	Lower limit
A2	-	Upper limit
[A]	-	Matrix of attenuation coefficients
API	-	American Petroleum Institute
ASME	-	American Society of Mechanical Engineer
CIPS	-	Close Interval Potential Survey
C_{air}	-	Ultrasonic speed in air
DAQ	-	Data acquisition
DCVG	-	Direct Current Voltage Gradient
D, d	-	Diameter, dimension
E	-	Error
ERT	-	Electrical Resistance Tomography
ECT	-	Electrical Capacitance Tomography
EMAT	-	Electromagnetic acoustic transducer
EC	-	Eddy current
EFM	-	Electrical Field Mapping
E	-	Weld joint factor
f	-	Frequency
F	-	Design factor
FSM	-	Field Signature Method
FBE	-	Fusion bonded epoxy
GPP	-	Gas Processing Plant
ICS	-	Internal Corrosion Sensors MFL- Magnetic Flux Leakage

I	-	Intensity
K	-	Constant
k	-	Rate
kHz	-	Kilohertz
L	-	Length
LBP	-	Linear Back Projection
LED	-	Light Emitting Diode
[M]	-	Matrix of measurement values
M	-	Measurement value or output
MIT	-	Magnetic Induction Tomography
MTM	-	Magnetometry Tomography Method
MMM	-	Metal Magnetic Memory
MHz	-	Megahertz
N	-	Near field length
NPS	-	Nominal pipe size
NDT	-	Non Destructive Testing
NACE	-	National Association of Corrosion Engineers
SSPC	-	Society for Protective Coatings
NGV	-	Natural gas vehicle
O	-	Orange
P	-	Percentage of energy
PE	-	Polyethylene
r	-	Radius
R	-	Regression
RP	-	Recommended Practices
S	-	Circumferential length
SSGP	-	Sabah and Sarawak Gas Pipeline
SCZ	-	Stress concentration zone
[S]	-	Sensitivity matrix
t	-	Time of sound travel, wall thickness
T	-	Temperature
TOF	-	Time-of-flight
V	-	Velocity, voltage
Wt	-	Weight

x	-	Distance
Y	-	Yellow
Z	-	Acoustic impedance

Superscript

α	-	Attenuation coefficient
T	-	Transpose
x	-	Distance

Subscript

a	-	Actual
att	-	Attenuation
B	-	Blue, black
i	-	Incident
m	-	Measured
o	-	Initial
r	-	Reflected
t	-	Transmitted, time
1	-	Medium 1
2	-	Medium 2

Greek symbols

λ	-	Wavelength
ρ	-	Density
θ	-	Angle of divergence

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Oil and gas are the natural resources that served as the energy source of most countries economic growth (Bonny *et al*., 2008). Many rely mainly to these natural resources for economic development of their countries. The natural resources are transported to the consumers throughout pipelines as shown in Figure 1.1. It is really important to ensure that the natural resources can be transported safely from its original plant or storage through extended pipelines, which spread throughout the countries to the consumers. The smooth transportation of the products such as from gathering system, transmission and onshore pipeline are very important in order to meet its operational needs and business growth of oil and gas industries. Pipeline is the preferred mode of transportation of oil and gas for a short distance because of its efficiency and low transportation cost compared to other methods such as tanker, pipeline barge, rail and truck (Kennedy, 1993). For a long distance of transportation, tanker is more effective in terms of its operational cost. Therefore, pipeline is the strategic assets that need to be maintained and evaluated for the operational time interval (Global, 2014). The network of pipelines is certainly out of rates due to its cost effectiveness, higher dependability of safety and security with environmental friendliness over extensive distances (Hossam, 2010).

The inner diameter of oil and gas pipelines are typically from 100 to 1220 mm (4 to 40 inches) and are made from steel, iron, copper or plastic (Mohitpour *et al*., 2003). These pipelines are either located underground or aboveground transportation system, where for underground pipeline; it is usually buried at a minimum depth of 1000 mm to ensure the safety of the natural resources and its surroundings.

Figure 1.1 Oil and gas pipeline (Bonny *et al.*, 2008)

It is known that pipeline systems provide the most efficient and safest means for the distribution and transportation of large quantities of oil and gas (Beller and Heittrich, 1997). However, pipelines age are severe in deterioration with time due to corrosion or the appearance of defects or flaws (Beller *et al*., 2001). The risks of pipeline failure need to be analyzed to ascertain the extent of the threats that could damage the pipe for the purpose of pipeline assessment (Mohd Ali Napiah, 2009). Corrosion is one of the most important mechanical integrity issues as it is the leading cause of pipe failure in oil and gas industry (Nicola *et al*., 2012). The external surface of pipe wall is the coating layer, which is known as protective surface for corrosion control (Nanetti, 2006). In order to ensure the effectiveness of corrosion protection of pipe for pipeline integrity, it is necessary for owner or manufacturer of pipe to have a reliable coating surface or insulation material, which complies with the standard (Beller and Hettrich, 1997). Figure 1.2 shows the coating affinity done on a pipeline in industry by the inspector.

Figure 1.2 Pipeline coating (Beller *et al*., 2001)

The National Association of Corrosion Engineers (NACE) and the Society for Protective Coatings (SSPC) are professional organizations involved in the industrial coatings industry. The flaws in the coating lead to the protective coating failures which will contribute to such as corrosion, rusting and pitting. A variety of flaws or coating faults can develop in the external pipe over the time due to the harsh environment such as surrounding temperature and soil condition (Beller *et al*., 2001). Pipe above ground usually faced with different whether such as surrounding temperature, lightening and earth quake which can affect external wall of the pipe. Besides, defects can also occur during pipeline construction before the pipe was laid in the ditch (Pikas and Shoaf, 2010).

Holidays, cracks, air bubbles, delamination and notches are typical flaws or coating faults. As stated in America Society of Mechanical Engineer (ASME B31.8 for Gas Transmission and Distribution Piping System), holiday is caused by discontinuity in the protective coating that exposes unprotected surface to environment (Code for pressure piping in 805.2.5), whereas notches is caused by the mechanical damage during manufacture and transportation handling (Code for pressure piping in 841.2.4). Pipe failure may be occurred if the flaws were not detected earlier during the construction phase (Joseph and William, 2010). Failures may lead to highly repair cost. All of these problems are easily detectable either during the coatings procedure or as part of the maintenance program. According to

ASME B31.8 for Gas Transmission and Distribution Piping System (Code for pressure piping in 841.2.2) for underground pipeline, most of the inspections on coating and pipe surface are conducted before it lowered into the ditch to find coating lacerations that indicate the pipe might have been damaged after being coated. Figure 1.3 shows the flaws existence on the pipe surface mainly on coating layer.

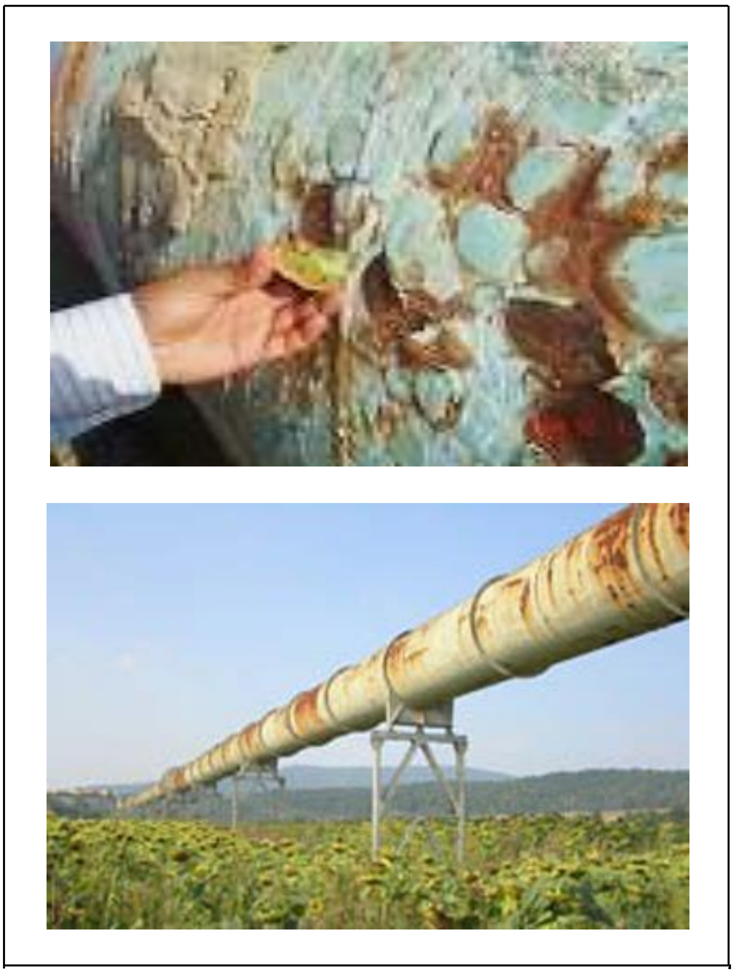

Figure 1.3 Flaws on pipe surface (Beller *et al*., 2001)

In pipe maintenance program, pipeline inspection is a key factor to optimize maintenance procedures (NDT Global, 2014). Non-Destructive Technique (NDT) has been used as a method to inspect pipeline over the last three decades (Beller *et al*., 2001). There are four common methods used in NDT such as radiography, eddy-current, magnetic particle and ultrasonic testing as (Zhang *et al*., 2007). Figure 1.4 shows one of the examples of NDT method applied on pipeline.

Figure 1.4 Varies of pipe inspections (Zhang *et al*., 2007)

Non-destructive Testing (NDT) plays a significant method to ensure the structural components and systems perform their function well. The NDT technique can examine the material conditions and irregularities that lead to pipeline failures. The tests do not affect the object to be inspected by which it provides a good balance between quality control and cost effectiveness. Among the NDT methods, the ultrasonic method is widely used for detecting internal flaws with high degree of certainty (Blitz and Simpson, 1996). It is the most applicable and known method applied by industries for pipeline inspection due to its effective measurement regarding to ease of operation, low cost, high sensitivity for small flaw and other advantages (Li and Rose, 2002).

1.2 Ultrasonic Testing

Ultrasonic is a sound waves that has frequency higher than human audible range, which is greater than 18 kHz (Blitz and Simpson, 1996). It has been used for plastics welding, medicine, jewelery cleaning and NDT pipe inspection. In the ultrasonic inspection, low amplitude of ultrasonic waves are propagated through a material to measure either the time of travel or any change of intensity for a given distance. The applications of ultrasonic include of distance gauging, flaw detection and measuring parameters which are related to the material structure (Blitz and Simpson, 1996). In industrial application, most of ultrasonic testings are used for flaws detection. Since 1940s, it is known that the transmission of sound waves through solid materials has been used to detect hidden cracks, voids, porosity, and other internal discontinuities in various type of material (Lee *et al*., 2010). Ultrasonic allows the accurate measurement of the pipe wall thickness based on sound velocity and attenuation measurements (Subramaniam, 2006).

Ultrasonic testing is a recognized technology as it offers a high level of accuracy that can be achieved if competently performed (Corrview, 2012). Three basic properties of wavelength, frequency and velocity are utilized during wave's propagation in any medium. The wavelength is inversely proportional to the frequency. There is a significant effect of the ultrasonic wavelength towards the probability of detecting a discontinuity. There are four principle modes for ultrasonic propagation, which are longitudinal, shear, surface and plate waves (Subramaniam, 2006). These modes of propagation will be dependent on the medium of waves propagated. Ultrasonic waves are so capable of detecting deep and small flaws as it can penetrate into most materials well with high sensitivity technique. There are several advantages of ultrasonic testing as stated by Charles (2003). These advantages make the ultrasonic testing as an excellent method for pipeline inspection. The advantages are listed as follow;

i) Exceptional sensitivity by allowing the detection of very small flaws.
ii) High accuracy of flaws detection within ± 0.1 to 0.2 mm
iii) Harmless operation to nearby personnel, equipment and materials inspected.
iv) Highly automated and precise with 95% confidence level in identifying reflector position, size and shape.

1.3 Process Tomography

Tomography can be defined as a technique to produce cross-sectional images of an object by taking the measurement around the periphery of the object. The word tomography comes from the Greek word ‘tomos’ means ‘to slice’ and ‘graph’ means ‘image’(William and Beck, 1995). A cross-sectional image of the object monitored is called a tomogram, while the equipment that generates the image is a tomography. It is relatively fast and simple to operate, has a rugged construction and is sufficiently robust to most of the industrial environments. The tomography technique is widely used as a medical diagnostic technique (Seeram, 2000). However, it has been extended to outside of the medical field by the concept of process tomography with non-invasive way of imaging (Chaouki *et al*., 1997). It is then applied in the industrial to examine the industrial process such as stirred reactors, separators, flows in pipe and pipeline integrity. In research worldwide, process tomography has been a recognized over two decades for process measurement and control in some related industrial application (Arshad Amari *et al*., 2011). Tomography technology involves the acquirement of measurement signals from non-intruding sensors located on the boundary of an object. The techniques are concerned with extracting information to obtain a cross sectional image.

In oil and gas industries, critical information on characterization of multiple flows, separation of multiphase components and process vessels can be provided from process tomography. There are many different methods used in process tomography, e.g. ultrasonic imaging, electrical resistance tomography (ERT), electrical capacitance tomography (ECT) and magnetic induction tomography (MIT) (Abdul Rahim *et al*., 2006). The applications of ultrasonic tomography technique for flaw detection in pipeline are limited as this technology is still in its infancy (Chen and Sanderson, 1996). The background history of success in a variety of non-tomographic applications can be seen such as in process measurement (Asher, 1983; Lynnworth, 1989; Plaskowski *et al*., 1992; Hoyle and Luke; 1994); and in non-destructive testing (McMaster, 1963; Silk, 1984). The ultrasonic process tomography is convenient for imaging as the differences in density and elasticity of the object offer the most needed sensing possibility (William and Beck, 1995).

The tomographic imaging can provide an opportunity to unravel the complexities of structure without invading the object (Dyakowski, 1995). The suitable algorithm is selected to perform the image reconstruction (Natterer, 1986). It is concerned with the information relating to two dimensions or three dimensions such as number of projections and derivations require information. Most of ultrasonic tomography techniques are applied for flow measurement such as investigated by Abdul Rahim *et al*. (2004), Fazalul Rahiman *et al*. (2006), Brown *et al*. (1995), Yang *et al*. (1999), Chen and Sanderson, (1996) and others. For monitoring flaws or defect using ultrasonic tomography technique, there are very limited studies or researches done on this area of inspection. It is due the requirement of computational power and data storage for image reconstruction system (Hall *et al*., 1999). However, this technique is very effective and reliable due to overall cost and high resolution to obtain an image of the test specimen (Abdul Rahim *et al*., 2004).

1.4 Problem Statement

Pipeline companies have an impressive safety record due to the proactive role of standards and inspection of pipelines. The pipeline structures represent a high capital venture and any risk of deterioration need to be avoided as it can cause environmental risks and possible threats to life (Hossam *et al*., 2010). Since the pipelines are aging, there is a great need to ascertain defects or flaws such as corrosion, pitting, holiday, cracks, gouges, grooves and notches that can cause potential problems to pipe failure (Khaleel and Simonen, 2000). Several factors have been identified that can lead to the corrosion of buried pipeline, such as soil conditions, changing of temperature, pipe coatings, pipe pressure, stresses and cyclic loading effects (Ginzel *et al.,* 2002). While for above ground pipe, the variety of changing environmental conditions lead to external pipe wall damage such as corrosion, crack or any irregularities existences. It is known that coating is one of protective layer from corrosion, keeping the system in operation and avoid leaks or failure (Toews and William, 2011). If the signs of defects or faults can be detected earlier, accidents can be prevented such as energy dissipation, economic loss and seriously polluted surrounding.

According to ASME B 31.8 for Gas Transmission and Distribution Piping System (Code for pressure piping in 861.1.1), the coating shall be visually inspected for defect or flaws such as holiday, corrosion, crack, notches, pinhole and delamination before the pipe is lowered into the ditch. Pipeline leakage may also lead to disaster such as fire and fatality if the pipeline is located near human population area (Richard *et al.*, 2008). The need for technologies to monitor pipelines is driven by threats to pipeline integrity. Early monitoring is needed for these threats in order to prevent incidents and maintain integrity (Teitsman, 2004). Pipe inspection is vital to manage aging assets and improve assets optimization as to extend lifespan of the pipe for product transportation. Special inspection tools for pipeline inspection have been developed over the last three decades and non-destructive-testing techniques (NDT) being introduced into the market (Beller *et al*., 2001).

NDT is a well-known tool used in industry for materials assessment, structural integrity test and manufacturing control (Li and Rose, 2002). It can characterize material conditions and flaws without any damage, which balance between quality control and cost-effectiveness without affecting the product. The common NDT applied in industry are radiography, eddy-current, magnetic particle and ultrasonic testing (Zhang *et al*., 2007). The ultrasonic NDT provide advantages such as low cost, ease of operation, high sensitivity and others which classified as the most efficient method for pipe inspection (Li and Rose, 2002). However, most researches conducted in ultrasonic testing are for localized flaw detection purpose and the result produced is basically on analysis of flaws characterization. Moreover, this application commonly used the sensor which is in contact with the test specimen using a liquid coupling layer (Brown and Reilly, 1996).

In industry, the overall image of pipe being inspected is needed in order to view or predict the exact location of the problem encountered with the pipe. Recently, there is still no research done on producing the tomographic image of pipe profile based on its thickness due to the flaws existence. Better imaging technique is required to visualize a clear image on the inspected pipe. Tomography is the most beneficial technology that can be applied to solve the problem as this technique involved with the image reconstruction system. Tomography technique is very efficient and reliable due to overall cost and high resolution to obtain an image of the test specimen (Abdul Rahim *et al*., 2004). Generally, a tomography system consists of sensor system, data acquisition system, display unit and image reconstruction system (Fazalul Rahiman et al., 2006).

Therefore, a research on ultrasonic tomography technique has been carried out to monitor flaw on pipe, which is considered as a new technique in pipeline inspection area. A reliable ultrasonic tomographic instrumentation system is developed for monitoring flaws on pipeline. A complete instrumentation system with ultrasonic tomography tool and the image reconstruction system are developed for monitoring flaws on pipe. The ultrasonic tomography tool will be modelled and fabricated for the inspection purpose. The image of the pipe profile with the flaws existence will be reconstructed based on suitable algorithm through image reconstruction system by programming using MATLAB software.

1.5 Objectives of Study

The objectives of this research are:

1. To develop a non-destructive ultrasonic tomography system (reflection mode) for monitoring flaws on pipeline surface by modelling.
2. To design and develop a complete tomographic instrumentation system from ultrasonic tomography tool to image reconstruction system (programming).
3. To develop an application program with suitable algorithm for reconstructing tomographic image of pipe profile.

4. To generate two dimensional image of cross-sectional pipe (circumference) to visualize flaws on the pipeline surface.

1.6 Scope of Study

The overall scopes for the development of ultrasonic tomographic instrumentation system consists of the work on designing the instrumentation system and reconstructing the image (programming).

1. Identifying basic characteristics of ultrasonic signal and its behavior based on reflection as the ultrasonic sensing mode by conducting a preliminary testing on ultrasonic sensor used.
2. Designing of the ultrasonic configuration and sensing system by mathematical modelling on the following components;
    a) The sensor fixture design which includes the type of sensor (transceiver) and its frequency, sensors arrangement geometry, and the number of sensors on the ultrasonic ring.
    b) The ultrasonic signal behaviours for transmission, reflection and attenuation based on percentage of energy coefficient.
    c) Image grid estimation for image pixel of ultrasonic signal produced by each sensor.
3. Setup a conditioning circuit with a complete transceiver circuitry with data acquisition system (Pico Scope display).
4. Conducting several experiments on distance calibration and monitoring flaws on pipe.
5. Analyzing the acquired voltage from data acquisition to determine distance travelled by the ultrasonic signal (data interpretation).
6. Performing forward and inverse problem for the basic of image reconstruction system.

7. Execute a suitable algorithm to reconstruct the image through MATLAB simulation and programming work based on physical properties of the object.
8. Generating the tomogram image of pipe profile with the flaws existence (circumference) using appropriate number of projection and array of pixel for high resolution image (MATLAB programming).

1.7 Limitations of the Instrumentation System

In this study, the developed ultrasonic tomography system has several limitations;

1) The ultrasonic instrumentation system is designed and applied for monitoring flaw on pipe for aboveground pipeline and also during pre-installation of underground pipe inspection.
2) In this research, the instrumentation system is specifically designed for 8 inch pipe size with fusion bonded epoxy coating material due to availability of 8 inch of gas pipe and applicable for aboveground pipeline (City Gate or transmission line, District and Service stations).
3) The amount of sensors mounted around the pipe is based on the sensor specifications (image grid, diameter and minimum distance of detection from sensor to coating).
4) The ultrasonic sensor used is a type of transceiver sensor of 390 kHz (both transmitted and receiving signal) with the highest resolution of 0.4 mm change in distance of detection.
5) The ultrasonic sensing ring can be used for any pipe size of aboveground pipeline system by rearrange the sensor position based on image grid or beam angle and distance from sensor to the pipe surface as required.
6) The reflection mode is used for ultrasonic signal propagation as the ultrasonic ring is contactless to the pipe surface.
7) The coating of the pipe can be any type of material as long as there is highly mismatch impedance between air medium and coating material or surface.

8) In image reconstruction system, the image resolution is dependent on the measurement values obtained which is based on the number of sensors used
9) The accuracy of the defect location and size is based on number of sensor used in the system.

1.8 Significant of Study

Pipelines are prone to degrade over the years as it exposed to harsh environment which lead to corrosion problem, either for underground or aboveground natural gas pipeline (Beller *et al*., 2001). Corrosion problem is one of the main causes of pipeline failures in oil and gas industry which affects a significant portion (80%) of annual maintenance costs (Nicola *et al*., 2012). Protective coating plays a critical role in shielding pipeline from corrosion, keeping the system in operation and to avoid leaks and failure (Toews and Williams, 2011). Coating layer defense against accelerated corrosion occurred within the pipe wall. It is very essential for external pipe wall protection from the harsh surrounding environment due to the change in whether, wind struck, and earth quake (Beller *et al*., 2001). Earlier detection on these flaws must be carried out in order to maintain the coating layer and to avoid damage on pipe wall which affect the pipe thickness. The deficiency in maintenance of natural gas pipelines can lead to property and life threatens which are resulting from the fire and explosion due to the pipeline leakage or ruptured (Hossam, 2010).

Aboveground pipeline system which is mostly for distribution gas piping is severe to pipe failure due to the change in weather (Beller *et al*., 2001). Therefore, it is important to conduct the pipe inspection within a certain period of installation to ascertain the coating and pipe condition. The inspection on pipe condition could sustain the design lifespan due to corrosion and pipe failure. The current methods used to control corrosion and pipe failure are not sufficient due to inapplicable in some condition and need improvement (Nicola *et al*., 2012). For the purpose of external pipe wall inspection, non-destructive ultrasonic tomographic instrumentation is designed to monitor flaws circumferentially on pipeline as an earlier prevention method to avoid corrosion from occurred. The change in external pipe wall thickness can be seen through the detected flaws by reconstructing the image of the circumferential pipe profile.

The ultrasonic tomography system is mainly used or applied for aboveground pipeline inspection. In addition, it can also be used for pre-installation inspection of underground gas pipeline as an earlier monitoring to make sure the coating and pipe thickness is satisfied with the requirement. It is important to inspect the coating layer with pipe wall thickness as an earlier stage before the pipe is installed into the ditch to maximize the pipe protection towards corrosion problem and to avoid rapid corrosion occurred due to corrosive environment. Besides, this instrument can be used by pipeline manufacturer to monitor their coating product from any defect and thus improve product quality. From the measurements of ultrasonic sensors, the image of the inspected pipe will be reconstructed to visualize the tomogram image of circumferential pipe profile (flaws and wall thickness). The image of pipe profile is important to verify the coating and pipe wall condition (thickness) are complied with the standard or required thickness. It is significant to detect any defects or flaws that will eventually lead to corrosion at the earliest possible stage of pipe installation. The protection of pipeline prior to the flaws existing on pipe surface is necessary in order to reduce corrosion problem within the external pipe wall, which result to long-term operation, minimize maintenance and prevent costly service disruptions (Kher, 1996).

1.9 Organization of Thesis

This thesis will discuss on development of ultrasonic tomographic instrumentation system for monitoring flaws on pipeline, which further to reconstruct a tomographic image of cross-sectional pipe inspected. The thesis consists of five chapters, the introduction, the literature review, research methodology, results and discussions, conclusion and recommendations.

Chapter 1 presents an introduction of research overview which discusses on research background, where ultrasonic testing and process tomography has been highlighted. It is continuing with the problem statement, significant of study, the research objectives and scope and finally the limitation of the system are also been addressed.

Chapter 2, which is a literature study, describes on several topics that related to this study based on historical, researches and theory presented. The overview on pipeline system in oil and gas industry, pipeline inspection techniques, ultrasonic characterization and ultrasonic inspection techniques are highlighted throughout this chapter. Besides, the ultrasonic tomography and image reconstruction technique are also been reviewed at the end of this chapter.

Chapter 3 explains on the methodology of this research which illustrates on the modelling and designing of a complete ultrasonic tomographic instrumentation system. Apart from that, the basic ultrasonic tomographic image reconstruction process and the image reconstruction algorithm for the system were briefly summarized. The procedures of some experimental works carried out to verify the capability of the system also describes throughout this chapter.

In Chapter 4, the results and discussion are presented from the experimental works conducted using the ultrasonic tomographic instrumentation system. Some experiments were carried out to investigate the capability of the system and to obtain the required data for image reconstruction purpose. Here, the data is analyze and presented in an appropriate manner. The tomogram images of overall pipe profile being inspected are visualized in this chapter. The results achieved from the experimental works and the image reconstructions are discussed. The results are analyzed based on measurement accuracy, capability of flaws detection and images resolution.

Chapter 5 is the final part of the thesis, which represents the conclusion and the recommendation for the future work based on the achievement from this research work.

REFERENCES

Abbaszadeh, J., Abdul Rahim, H., Abdul Rahim, R., Sarafi, S., Ayob, M.N., and Faramarzi, M. (2013). Design Procedure of Ultrasonic Tomography System with Steel Pipe Conveyor. *Sensor and Actuators A.* 203, 215-224.

Abdul Hakim bin Kassim (2008). *Ultrasonic Motion Detector*. Bachelor Degree, Universiti Teknologi Malaysia, Skudai.

Abdul Rahim, R., Fazalul Rahiman, M.H., and Chan, K.S. (2004). On Monitoring Liquid/Gas Flow Using Ultrasonic Tomography. *Journal Teknologi*. 40(D), 77-88.

Abdul Rahim, R., Nyap, N.W., and Fazalul Rahiman, M.H. (2007). Hardware Development of Ultrasonic Tomography for Composition Determination of Water and Oil Flow. *Sensor& Transducer Journal*. 75, 904-913

Abdul Rahim, R., and Green, R.G. (1998). Optical Fibre sensor for process tomography, *Pergamon*. 6, 1365-1371

Al-Salaymeh, A., and Durst, F. (2004). Development and Testing of a Novel Single Wire Sensor For Wide Range Flow Velocity Measurements. *Measurement Science Technology*. 15, 777–788.

Alpha Pipeline Integrity Services (2012). *Close Interval Surveys (CIS) & Direct Current Voltage Gradient (DCVG) Surveys.* [Brochure]. Texas: Alpha Pipeline Integrity Services Inc.

ANS Advanced NDT Solution (2015). *LRUT-Long Range Ultrasonics*. [Brochure]. Co Westmeath: Ansndt.

Antoniotti, K. (2013, August 03). City not privy to pipeline locations inside own borders. *Ohio.com*. Retrieved June, 20 2014, from http://www.ohio.com

Arshad Amari, H., Abdul Rahim, R., Fazalul Rahiman, M.H., and Puppanathan, J. (2011). Front-End Design of an Ultrasonic Tomography Measurement System. *Jurnal Teknologi (Sains & Kej.).* 54, 289-298.

Bahadir, S.K., Kalaoglu, F., Thomassey, S., Cristian, I., and Koncar, V. (2011). A study on the Beam Pattern of Ultrasonic Sensor Integrated to Textile Structure. *International Journal of Clothing Science and Technology*. 23(4), 232-241.

Baskaran, G., Balasubramaniam, K., and Krishnamurthy, C.V. (2006), Inspection Using Shear Wave Time of Flight Diffraction (S-TOFD) Technique. *Review of Quantitative Nondestructive Evaluation*, *25*, 98-102. American Institute of Physics.

Barjaktarovic, M., Petricevic, S., and Radunovic, J. (2007). High performance coated board inspection system based on commercial components. *Journal of Instrumentation*. 2, 1-14.

Beaver, J.A., and Thompson, N.G. (2006*).* External Corrosion of Oil and Natural Gas Pipelines. In Speight, J.G. (Ed.) *ASM Handbook Corrosion: Environments and Industries* (pp. 1015-1025). Ohio, US: ASM International, Materials Park

Beck, M.S., and Williams, R.A. (1998). Process Tomography- The State of Art. *Transducer and Instrumentation*. 20(4): 163-177.

Beck, M.S., and Williams, R.A. (1996). Process Tomography: A European Innovation and Its Applications. *Meas. Sci. Technol. 7*: 215-224.

Barbian, A. and Beller, M. (2012). In-Line Inspection of High Pressure Transmission Pipelines: State-of-the-Art and Future Trends. *18th World Conference on Nondestructive Testing*. 16-20 April 2012. Durban, South Africa

Beller, M, (2007). *Pipeline Inspection Utilizing Ultrasound Technology: On The Issue of Resolution.* Unpublished note, Pigging Products and Services Association.

Beller, M., Holden, E., and Uzelac, N. (2001). Cracks in Pipelines and How to Find Them. *Pipes and Pipelines International*, 46, 26-34. Scientific Surveys Ltd.

Beller, M., and Hettrich, U. (1997). Intelligent Pigging of Pipelines: A Turkey Approach. *PennWell Conferences and Exhibitions.* 28-30 January. Houston, TX United States, 284-290.

Bernama. (2013, October 19). 482 workers evacuated in Ayer Keroh gas pipe leak. Borneo Post Online, from http://www.theborneopost.com.

Bingham, J., and Hinders, M. (2009). Lamb Wave Detection of Delamination in Large Diameter Pipe Coatings. *The Open Acoustics Journal.* 75-86.

Bonny, B.N., Umeadi, K.G., and Jones (2008). The Development of An Intelligent Sensor for the Monitoring of Pipeline System Integrity. *SPE Russian Oil & Gas Technical Conference and Exhibition* 28-30 October. Moscow, Russia, 1-10.

Bradley, R., and Coutlakis, J. (2014, January 01). Asheville gas line explosion cost $825,000. *Citizen-Times*. Retrieved Feb 11, 2014, from http://www.citizen-times.com.

Brown, G.J., and Reilly, D. (1996). Ultrasonic Tomographic Imaging of Solid Objects in Air using an Array of Fan-Shaped-Beam Electrostatic Transducers. *Ultrasonics*. 3*4*, 111-115.

Brown, G. J., Reilly, D., and Mills, D. (1995). Ultrasonic Transmission-Mode Tomography Applied to Gas/Solids Flow. *Proceedings of Process Tomography '95: Implementation for Industrial Processes*. 176-186.

Brown, G. J., Reilly, D., and Mills, D. (1996). Development of an Ultrasonic Tomography System for Application in Pneumatic Conveying. *Measurement Science Technology.* 7, 396-405.

Carvalho, A.A., Rebello, J.M.A., Souza, M.P.V., Sagrilo, L.V.S., and Soares, S.D. (2008). Reliability of Non-Destructive Test Techniques in the Inspection of Pipelines used in the Oil Industry. *International Journal of Pressure Vessels and Piping*. 85, 745-751.

Censor, Y. (1983). Finite series-Expansion Reconstruction Methods. *Proc. of IEEE*. 71(3), 409-419.

Chaouki, J., Larachi, F., and Dudukovic, M.P. (1997). Non-invasive Tomographic and Velocimetric Monitoring of Multiphase Flows. *Industrial & Enginering Chemical Research.* 36 (11), 4476-4503.

Charles. J.H. (2003). *Ultrasonic Testing*. In: Robert, C.M. and Samuel A. W. *Handbook of Non-Destructive Evaluation.* (pp. 301-416). US: McGraw-Hill.

Chen, Z.X., and Sanderson, M.L. (1996). Ultrasonic Tomography for Process Measurement. *IEEE Instrumentation and Measurement Technology Conference.* 4-6 June. Brussels, UK, 659-662.

Chiam, T.K. (2006). *Embedded System Based Solid-Gas Mass Flow Rate Meter Using Optical Tomography*. Master Degree, Universiti Teknologi Malaysia, Skudai.

Choi, J.Y., Lim, H., and Yi, B. (2006). Semi-Automatic Pipeline Inspection Robot System. *SICE-ICASE International Joint Conference.* 18-21 October. Busan, Korea: IEEE, 2266 – 2269.

Christi, C. (2010, December 17). Gas Line Fire Explosion Critically Burns Man's Face. *Kiii tv*. Retrieved June 20, 2014, from http://www.kiiitv.com.

Corrocont Limited (2016). *LFET-Low Frequency Electromagnetic Testing.* [Brochure]. Hungary: Navan Media Ltd.

Davies, J., and Cawley, P. (2009). The Application of Synthetic Focusing for Imaging Crack-Like Defects in Pipelines Using Guided Waves, *IEEE Transactions on Ultrasonic Ferroelectrics, and Frequency Control*. 56, No. 4.

Dickin, F.J., and Wang, M. (1995). Impedance Sensors-Conducting Systems In: Williams, R. A. and Beck, M. S. (Eds). *Process Tomography: Principles, Techniques and Applications*. Oxford: Butterworth-Heinemann. 63-84.

Didas, J. (2011). *Technical Report on Fundamental of Pipeline Coating:* AUCSC.

Dixon, S., Lanyon, B., and Rowlands, G. (2006). Coating Thickness and Elaastic Modulus Measurement Using Ultrasonic Bulk Wave Resonance. *Applied Physics Letters 88*.

Duck, F.A., Baker, A.C., and Starritt, H.C. (1998). *Ultrasound in Medicine*. Institute of Physics Publishing: CRC Press.

Dyakowski, T. (1995). *Tomography in a Process System*. In: Williams, R. A. and Beck, M. S. (Eds). *Process Tomography: Principles, Techniques and Applications*. Oxford: Butterworth-Heinemann. 13-37.

Dugdale, P., Green, R.G., Hartley, A.J., Jackson, R.G., and Landauro, J. (1992). Optical sensors for process tomography. *European Concerted Action on Process Tomography*. March. Manchester, 26-29.

Elmy Johana Binti Mohammad (2012). *A Segmented Capacitance Tomography for Visualising Material Distributions in Pipeline Conveying Crude Palm Oil.* Doctor Philosophy, Universiti Teknologi Malaysia, Skudai.

Ed Ginzel (1999). Ultrasonic Inspection 2 Training for Non-destructive Testing - Variables Affecting Test Results. *NDT.net,* 4(6).

El Youbi, F., Grondel, S., and Assaad, J. (2004), Signal Processing for Damage Detection Using Two Different Array Transducers. *Ultrasonics.* 42, 803-806.

Faiz bin Fadhil (2011). *Charactertsttc Study of Ultrasonic (Time-of-Flight) on Different Types of Surface.* Bachelor Degree, Universiti Teknologi Malaysia, Skudai.

Fazalul Rahiman, M.H., Abdul Rahim, R., and Rahim, H.A. (2011). Gas Hold-up Profiles Measurement using Ultrasonic Sensor. *IEEE Sensors Journal*. 11(2), 460–461.

Fazalul Rahiman, M.H., Abdul Rahim, R., Rahim, H.A., Mohamad, E.J., Zakariaa, Z., and Mujic, S.Z.M. (2014). An Investigation on Chemical Bubble Column using Ultrasonic Tomography for Imaging of Gas Profiles. *Sensors and Actuators.* B (202), 46-52

Fazalul Rahiman, M.H., Abdul Rahim, R., Abdul Rahim, H., Zakaria, Z., and Pusppanathan, M.J. (2014). A Study on Forward and Inverse Problems for an Ultrasonic Tomography. *Jurnal Teknologi.* 70(3), 113-117.

Fazalul Rahiman, M.H., Abdul Rahim, R., and Tajjudin, M. (2006). Ultrasonic Transmission Mode Tomography Imaging for Liquid/Gas Two Phase Flow. *IEEE Sensors Journal*. 6(6), 1706-1715.

Fazalul Rahiman, M.H., Abdul Rahim, R., Yaacob, S., Zakaria, Z., and Mann, R. (2009). A Comparative Study on Ultrasonic Transceiver Sensing Array for Bubbly Gas Holdups. Proceedings International Conference on Control, Instrumentation and Mechatronics Engineering (CIM '09). Melaka, Malaysia, 765-768.

Fazalul Rahiman, M.H., Abdul Rahim, R., and Zakaria, Z. (2008). Design and Modelling of Ultrasonic Tomography for two-Component High-Acoustic Impedance Mixture. *Sensors and Actuators*. A(147), 409-414.

Fazalul Rahiman, M.H., Abdul Rahim, R., and Zakaria, Z. (2008). Ultrasonic Process Tomographic Imaging Sensor: An Approach Utilizing Transceiver Method. *Proceeding of the International Conference on Computer and Communication.*

Fazalul Rahiman, M.H., Abdul Rahim, R., Abdul Rahim, H., and Nor Ayob, N.M. (2012). Design and Development of Ultrasonic Process Tomography. In Santos A. A. (Ed.) *Ultrasonic Waves* (pp. 211-226). Europe: InTech

Fowler, K.A., Hotchkiss, F.H.C., Yamartino, T.V., and Nelligan, T. (2012). Important Characteristics of Sound Fields of Ultrasonic Transducers. *Olympus NDT*. Retrieved 2013, from http:// www.olympus-ims.com.

Galbraith, J. (2012). *Assessment of the Capabilities of Long-Range Guided-Wave Ultrasonic Inspections*. Unpublished note, Long Range Ultrasonic Technology Group, NACE.

Gamio, J., and Aguilar, L. (2003). Parallel Realization of the Linear Back-Projection Algorithm for Capacitance Tomography using TMS320C6701DSP. *3rd World Congress on Industrial Tomography*. Banff, Canada, 648-653.

Gamma Petroleum Services (2013). *Pipeline Inspection Using Eddy Current Array Technology*. [Brochure]. Iraq: Gammaps.org

Garcia-Stewart, C. A., Polydorides, N., Ozanyan, K. B., and McCann, H. (2003). Image Reconstruction Algorithms for High-Speed Chemical Species Tomography. *Proceedings 3rd World Congress on Industrial Process Tomography*. Banff, Canada, 80-85.

George, C. (1967). *Nondestructive Testing: Ultrasonic Testing*. San Diego, California: General Dynamics.

George, L., and Lai, J. (2006). Ultrasound Physics: An Introduction. *AACA Pre-conference Workshop perioperative ultrasound.* 5-6 November. Sydney, 1-5.

Ginzel, R.K., and Kanters, W.W. (2002). Pipeline Corrosion and Cracking and the Associated Calibration Considerations for Same Side Sizing Applications. *e-Journal of Nondestructive Testing*. 7(7), 1-14.

Gloria, N.B.S., Areiza, M.C.L., Miranda, I.V.J., and Rebello, J.M.A. (2009). Development of A Magnetic Sensor for Detection and Sizing of Internal Pipeline Corrosion Defects. *NDT & E International Journal*. 42, 669-677.

Goh, C.L. (2005). *Real-Time Solids Mass Flow Rate Measurement via Ethernet Based Optical Tomography System*. Master Degree, Universiti Teknologi Malaysia, Skudai.

Green, R. G., Rahmat, M. F., Evans, K., Goude, A., Henry, M., and Stone, J.A.R. (1997). Concentration Profiles of Dry Powders in a Gravity Conveyor Using an Electrodynamic Tomography System. *Measurement Science Technology*. 8, 192-197.

Hall, I.D., McNab, A., and Hayward, G. (1999). Improved Ultrasonic Image Generation Through Tomographic Image Fusion. *Ultrasonics.* 37, 433-443.

Hamiltan, J.C. (2000). The Development of an EMAT based in-line Inspection System for the Detection of Stress Corrosion Cracks in Operating Pipelines. *GRI report*. 00/0184.

Hauptmann, P., Hoppe, N., and Puttmer, A. (2002). Application of Ultrasonic Sensors in the Process Industry. *Measurement Science & Technology*. 13, 73-83.

Hill, G. (2012, September 6). Natural gas pipeline explodes near Alice, Texas: owner. *Reuters.* Retrieved September 6, 2012, from http://www.reuters.com.

Hopkins, P. (2012). Why Failures Happen and How to Prevent Future Failures. *Journal of Pipeline Engineering*. 11(2), 77-91.

Hossam, A.K., and Hossam, A.G. (2010). Review of pipeline integrity management practices. *International Journal of Pressure Vessels and Piping*. 87: 373-380.

Hoyle, B.S. (1996). Process Tomography using Ultrasonic Sensor. *Measurement Science &. Technology.* 7, 272-280.

Hoyle, B.S. (1998). *Ultrasound Process Tomography- the prospect in food processing and inspection*. In: Povey, M.J.W and Mason, T.J. *Ultrasound in Food Processing* (pp. 66-81). London: Thompson Science.

Hoyle, B.S., and Xu, L.A. (1995). *Ultrasonic Sensors*. In: Williams, R.A. and Beck, M.S. *Process Tomography - Principles, Techniques and Application* (pp. 119-149). Butterworth: Heinemann Ltd.

Hsieh, J., Nett, B., Yu, Z., Sauer, K., Thibault, J.B., and Bouman, C.A. (2013). Recent Advances in CT Image Reconstruction. In Hsieh *et al* (Eds.) *Advance in CT Imaging*. Springer Science.

Ibrahim, S. (2000). *Measurement of Gas Bubbles in a Vertical Water Column Using Optical Tomography*. Doctor Philosophy, Sheffield Hallam University, UK.

Ibrahim, S., Md Yunus, M.A., Md Khairi, M.T. and Faramarzi, M. (2014). A Review on Ultrasonic Process Tomography System. *Jurnal Teknology.* 70(3), 1-5.

Idroas, M., Sapi'ee, N.F., Ibrahim, M.N., Md Zin, A.R. and Mohd Najib, S. (2011). "A comparison between linear back projection (transpose) and layergram back projection methods for image reconstruction in charge-couple device (CCD) based optical tomography," *Jurnal Teknologi (Sains & Kej.) Keluaran Khas*. 55(2), 23-31.

Idroas, M., Abdul Rahim, R., Green, R.G., Ibrahim, M.N. and Rahiman, M.H.F (2010). Image Reconstruction of a Charge Coupled Device Based Optical Tomographic Instrumentation System for Particle Sizing. *Sensors.* 10, 9512-9528.

Ihara, I. (2008). Ultrasonic Sensing: Fundamentals and its Applications to Nondestructive Evaluation. In Mukhopadhyay, S.C. and Huang, R.Y.M. (Eds.) *Sensors* (pp. 287-305). Berlin Heidelberg: Springer-Verlag.

Industrial Inspection Services (2016). *Magnetic Particle Testing*. [Brochure]. Bangladesh: iisndt.com

Ishimaru, A. (1990). *Wave Propagation and Scattering in Random Media*. New York: IEEE Press.

Jack Blitz and Geoff Simpson (1996). *Ultrasonic Methods of Non-Destructive Testing*. (1st ed.). London, UK: Champman & hall.

Jang, Y. Shin, S., Lee, J.W., and Kim, S. (2007). A preliminary Study for Portable Walking Distance Measurement System Using Ultrasonic Sensors. *Proceedings of the 29th Annual IEEE International Conference of the EMBS*, France. 5290-5293.

Kang, T., Lee, D.H., Song, S.J., Kim, H.J., Jo, Y.D., and Cho, H.J. (2011). Enhancement of detecting defects in pipes with focusing techniques. *NDT&E International*. 44, 178-187.

Kennedy J.L. (1993) *Oil and Gas Pipeline Fundamentals*. (2nd ed.) Tulsa, Okla: Penn Well Books.

Kercel, S.W., Jr, R.W.T., and Varma, V.K. (2003). Pipeline Flaw Detection with Wavelet Packets and Gas. *Proceedings of SPIE Intelligent Computing: Theory and Applications*. 5103, 217-227.

Khaleel, M.A., and Simonen, F.A. (2001). Effects of Alternative Inspection Strategies on Piping Reliability. *Nuclear Engineering and Design*. 197: 115-140.

Kim, D., Cho,Y., and Lee, J. (2010). Assessment Of Wall-Thinning In Carbon Steel Pipe By Using Laser-Generated Guided Wave, *Nuclear Engineering And Technology*, 42, 546-551.

Kikura, N.F.H., and Komero, M.T. (2007). Tomographic imaging of counter-current bubbly flow by wiremesh tomography. *Chemical Engineering Journal*. 130, 111-118.

Koh, Q (2012, August 01). Fatal Accidents at Petronas Sites Forces Relook at Safety Standards. *Rigzone*. Retrieved June 20, 2014. from http://www.rigzone.com

Krautkramer, J. (1977). *Ultrasonic Testing of Materials.* (2nd ed.). New York, U.S. Springer-Verlag.

Lee, J-R., Chia, C.C, Shin, H.J., Park, C-Y., and Yoon, D.J. (2010). Laser Ultrasonic Propagation Imaging Method in the Frequency Domain Based on Wavelet Transformation. *Optics and Laser in Engineering.* 49, 167-175.

Lee, J-R., Chong, S.Y., Jeong, H., and Kong, C-W. (2011). A Time-of-Flight Mapping Method for Laser Ultrasound Guided in a Pipe and its Application to Wall Thinning Visualization. *NDT&E International.* 44, 680-691.

Lesniak, J.R., Bazile, D.J., and Boyce, B.R. (1999). Coating Tolerant Thermography Inspection System. *Nondestructive Evaluation of Bridges and Highway II*. Proceeding SPIE. Newport Beach, CA.

Lewitt, R.M. (1983). Reconstruction algorithms: Transform method, *Proc. of the IEEE*. 71(3), 390-408.

Li, J., and Rose, J.L. (2002). Angular-Profile Tuning of Guided Waves in Hollow Cylinders Using a Circumferential Phased Array. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control.* 49(12), 1720-1729.

Li, W., and Hoyle, B.S. (1997). Ultrasonic Process Tomography using Multiple Active Sensors for Maximum Real-Time Performance. *Chemical Engineering Science*. 52, 2161-2170.

Licznerski, T.J., Jaronski, J., and Kosz, D. (2011). Ultrasonic System for Accurate Distance Measurement in the Air. *Ultrasonic 51*. 960-965. Engineering. 13-15 May. Kuala Lumpur, Malaysia, 1147-150.

Liu, L., and Ju, Y. (2010). A High-Efficiency Nondestructive Method for Remote Detection and Quantitative Evaluation of Pipe Wall Thinning Using Microwaves. *NDT &E International.* 44, 106-110.

Lovstad, A., and Cawley, P. (2011). The Reflection of the Fundamental Torsional Guided Wave From Multiple Circular Holes in Pipes. *NDT &E International,* 44. 553-562.

Luo,W., Rose, J.L., Velsor, J.K.V., Avioli, M., and Spanner, J. (2006). Circumferential Guided Waves Defect Detection in Coated Pipe. *Review of Quantitative Nondestructive Evaluation*. 25, 165-172.

Massa, P.D. (1999). Choosing An Ultrasonic Sensor for Proximity or Distance Measurement Part 2: Optimizing Sensor Selection. *Unpublished note,* Sensor Online.

McClements, D.J. (1995). Ultrasonic characterization of Foods. In Gaonkar, A.G. (Ed). *Characterization of Food: Emerging Methods* (pp. 93-106). Elsevier Science B.V.

Mistras Asset Protection Solution (2009). *Phased Array Inspection Services*. [Brochure]. US: mistrasgroup.com.

Mohd Ali Napiah, M.N., and Abdullah, A.M. (2009). Managing Integrity of Feed Condensate Pipeline: Online Internal Corrosion Monitoring via Electric Field Mapping (EFM)/Field Signature Method (FSM) Technique. *24th Gas Conference,* Buenos aires.

Mohd Aznan Shukri bin Mohd Safian (2006). *Integrity Assessment of Corroded Pipeline using In-Line Inspection Data*. Master Degree, Universiti Teknologi Malaysia, Skudai.

Mohd Fua'ad bin Rahmat (1996). *Instrumentation of Particle Conveying Using Electrical Charge Tomography*. Doctor Philosophy, Sheffield Hallam University, Sheffield, UK.

Mohd. Hafiz bin Fazalul Rahiman (2003). *Image Reconstruction using Transmission Mode of Ultrasonic Tomography in Water-particles Flow*. Bachelor Degree, Universiti Teknologi Malaysia, Skudai.

Mohd Hafiz Fazalul bin Rahiman (2005). *Non-Invasive Imaging of Liquid/ Gas Flow using Ultrasonic Transmission-Mode Tomography*. Master Degree, Universiti Teknologi Malaysia, Skudai.

Mohd. Muji, S.Z, Abdul Rahim, R., Fazalul Rahiman, M.H, Sahlan, S., Abdul Shaib, M.F., Muhammad Jaysuman and Mohammad, E.J. (2011). Optical Tomography: A Review on Sensor Array, Projection Arrangement and Image Reconstruction Algorithm. *International Journal of Innovative Computing, Information and Control.* 7(7), 3839-3856.

Mohd Saiful, A.R., and Mazeyanti, M.R. (2010). The Usage of Wireless Sensor Network for Early Detection Method of Corrosion on Buried Steel Gas Pipeline. *In Proceeding of Regional Conference on Knowledge Integration in ICT.*13-18

Moh'd Zaghal, R. (2007). *Car's Blind-Spot Collision Avoidance System using Ultrasonic Sensors and PIC Microcontroller*. Bachelor Degree, Jordan University of Science and Technology, Jordan.

Mohitpour, M., Golshan, H., and Murray, A. (2003). *Pipeline Design & Construction : A Practical Approach.* (2nd ed.) New York: ASME Press.

Muhammad, E.J. (2005). *Flame Imaging Using Laser Based Transmission Tomography*. Master Degree, Universiti Teknologi Malaysia, Skudai.

Nanetti, P. (2006). Coatings from A to Z. In Erlhoff, M. and Marshall, T. (Eds.) *Design Dictionary: Perspectives on Design Terminology. German:* BirkhauserVerlag AG.

Natterer, F. (1986). *The Mathematics of Computerized Tomography*. Germany: B G Teubner.

NDT Education Resource Centre (2001). *Information and Materials for NDT and NDE Technical Education*. [Brochure]. US: Iowa State University.

NDT Global (2014). *Crack Detection and Pipeline Integrity Solutions*. [Brochure]. Rusia: NDT Global.

NDT Global (2014). *Pipeline Inspection and Integrity Solution.* [Brochure]. Rusia: NDT Global.

Ng Wei Nyap. (2005). *Development of Ultrasonic Tomography for Composition Determination of Water and Oil Flow.* Master Degree, Universiti Teknologi Malaysia, Skudai.

Niese, F., Yashan, A., Izfp, F., Saarbrucken, and Willems, G.H. (2006). Wall Thickness Measurement Sensor for Pipeline Inspection using EMAT Technology in Combination with Pulsed Eddy Current and MFL. *NDT Systems & Services*, 1-10. ECNDT.

Nishino, H. (2010). A Feasibility Study on Pipe Inspection Using Ultrasonic Guided Waves for Maintenance of Nuclear Power Plants. *International Symposium on the Ageing Management & Maintenance for Nuclear Power Plants.* 184-198.

Olympus NDT. (2006). *Ultrasonic Transducers Technical Notes*. [Brochure]. US: Panametric-NDT.

Otero, R., Moreno, E., and Meza, B. (2011). Generation of Focused Ultrasonic Guided Waves for Nondestructive Testing of Structures. *5th Pan American Conference for NDT*. 2-6 October. Cancun-Mexico.

Pang, J.F. (2004). Real-Time Velocity and Mass Flow Rate Measurement Using Optical Tomography. Master Degree, Universiti Teknologi Malaysia, Skudai.

Pepperl Fuchs (2013). *Ultrasonic Sensor UB300-18GM40-I-V1*. [Brochure]. Germany: Pepperl Fuchs.

Petroliam Nasional Berhad (PETRONAS). (2014). *Asset Optimisation in Technology Products & Technical Solution*. [Brochure]. Malaysia: Petronas

Petroliam Nasional Berhad (PETRONAS). (2014). *Managing of Asset Facilities in Technology Products & Technical Solution*. [Brochure]. Malaysia: Petronas.

Pikas, J., and Shoaf, W. (2010). The Lightning Threat to Pipelines and Coatings. *The Journal of Pipeline Engineering*. 9, 191-196.

Polonsky, S., Shemer, L., and Barnea, D. (1999). Averaged and Time-Dependent Characteristics of the Motion of an Elongated Bubble in a Vertical Pipe. Int. *J. Multiphase Flow*. *25*, 795-812.

Pusppanathan, M.J., 1 Nor Ayob, N.M., Yunus, F.R., Sahlan, S., Abas, K.H. Rahim, H.A., Abdul Rahim, R., and Phang, F.A. (2013). Study on Single Plane Ultrasonic and Electrical Capacitance Sensor for Process Tomography System. *Sensors & Transducers*. 150, 40-45.

Raj, B., Rajendran, V., and Palanichamy, P. (2004). *Science and Technology of Ultrasonics*. (1st ed.) India: Alpha Science International Ltd.

Reinecke, N., Petrisch, G., Schmitz, D., and Mewes, D. (1998). Tomographic Measurement Techniques: Visualization of Multiple Phase Flows. *Chemical Engineering Technology*. 21, 7-18.

Richard K., and Jerry, W. (2008). *Digital Pipeline Leak Detection Using Fiber-optic Distributed Sensing (DTS)*. Westwick: Farrow Publishing.

Robertson, T.J., Hutchins, D.A., and Billson, D.R. (2002). Surface Metrology Using Reflected Ultrasonic Signals in Air. *Ultrasonics*. 39, 476-486.

Rose, J.L. (2002), A Baseline and Vision of Ultrasonic Guided Wave Inspection Potential, *Journal of Pressure Vessel Technology*. 124, 273-282.

Ruzairi bin Abdul Rahim (1996). *A Tomographic Imaging System for Pneumatic Conveyors Using Optical Fibres*. Doctor Philosophy, University of Sheffield, Hallam.

Rysco Corrosion Services (2015). *External Ccoating Indirect Inspection: AC Current Attenuation (ACCA).* [Brochure]. Canada: Creative pixel media.

Sagar, S.P., Hua, J.J., Rose, J.L. (2009). Ultrasonic Guided Wave Phased Array Inspection of Pipelines. *Proceeding of the National Seminar & Exhibition on Non-Destructive Evaluation.* 10-12 December. 229-232.

Seeram, E. (2000). *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*. (3rd ed.). US: Sounder Elsevier.

Seo, J.K., and Woo, E.J. (2013). *Nonlinear Inverse Problems in Imaging*. (1st ed.) India: John Wiley & Sons, Ltd.

Shawki, S. (2011). Above Ground Coating Integrity Assessment: Experience with SUMED Pipelines. In Boukharouba *et al*. (Eds). *Integrity of Pipelines Transporting Hydrocarbons* (pp. 311-321). Netherland: Springer-Science.

Shiozawa, D., Kubo,S., and Sakagami,T. (2006). Experimental Study on Applicability of Passive Electric Potential CT Method for Identification of Three-Dimensional Surface Crack, *JSME International Journal*. 4, 426-435.

Smith, L. M. (2001). Fundamentals of Holiday Detection. *Application Training Bulletin*, 37-40.

Sprawls, P. (1995). *The Physical Principles of Medical Imaging*, (2nd ed.) Madison: Wisconsin

Steiner, G., and Podd, F. (2006). A Non-Invasive and Non-Intrusive Ultrasonic Transducer Array for Process Tomography. *Proceeding of the XVIII IMEKO World Congress on Metrology for a Sustainable Development.* 17-22 September. Rio de Janeiro, Brazil, 1-6.

Subramaniam, C. V. (2006). *Practical Ultrasonics.* India: Alpha Science.

Sun, L., Yibo, Li, Shijiu, and Jin (2006). Study on Guided Ultrasonic Waves Propagating along Pipes with Fluid Loading. *6th World Congress on Intelligent Control and Automation*. Dalian, China: IEEE, 5037-5041.

Terzic, J., Terzic E., Nagarajah, R., and Alamgir, M. (2013). *Ultrasonic Fluid Quantity Measurement in Dynamic Vehicular Applications*. Switzerland: Springer- International.

Teitsma, A. (2004*). U.S Department of Energy No. DE-FC26-02NT41647.* Morgantown, US: Gas Technology Institute.

The American Society of Mechanical Engineers, ASME (2010). *B31.8*. USA: American National Standards Institute.

Thurston, R.N., Pierce, A.D., and Papadaki, E.P. (1998). *Reference for Modern Instrumentation, Techniques, and Technology: Ultrasonic Instruments and Devices I: Ultrasonic Instruments and Devices 1.* (1st ed.) US: Academic Press.

Toews, B., and Williams, S. (2011, July-Sept). Top 10 Pipeline Coatings maintenance Tips-The Formula for a Successful Project. *PetroMin Pipeliner*. Retrieved July-Sept, 2011, from http://www.safan.com.

Vedam, S. S., Keall, P. J., Kini, V. R., Mostafavi, H., Shukla, H. P., and Mohan, R. (2003). Acquiring a Four-Dimensional Computed Tomography Dataset Using an External Respiratory Signal. *Physics Medicine and Biology*. 48, 45–62.

Waltham. (2013, June 3). Olympus Introduces the UltraWave LRT Flaw Detection System using Guided Wave Technology. *Ndt.net*. Retrieved July, 2013, from http://www.ndt.net.

Wang, M. (1999). Three-dimensional Effects in Electrical Impedance Tomography. *Proceeding 1st World Congress on Industrial Process Tomography*. 410-415.

Wang, X., Tse, W. P., Mechefske, K. C., and Hua, M. (2010). Experimental Investigation of Reflection in Guided Wave-Based Inspection for the Characterization of Pipeline Defects. *NDT & E International*. *4*3, 365-374.

Warsito, W., Ohkawa, M., Kawata, N., and Uchida, S. (1999). Cross-Sectional Distributions of Gas and Solid Holdups in Slurry Bubble Column Investigated by Ultrasonic Computed Tomography. *Chemical Engineering Science*. 54, 4711-4728.

Warsito, W., and Fan, L. S. (2001). Neural Network Based Multi-Criterion Optimization Image Reconstruction Technique For Imaging Two and Three-Phase Flow Systems Using Electrical Capacitance Tomography. *Measurement Science Technology*. 12, 2198–2210.

West, R. M., Meng, S., Aykroyd, R. G., and Williams, R. A. (2003). Spatial-temporal Modelling for Electrical Impedance Imaging of a Mixing Process. *3rd World Congress on Industrial Process Tomography.* Banff, Canada, 226-232.

Willcox, M., and Downes, G. (2003). *A Brief Description of NDT Techniques.* Unpublished note, Insight NDT Equipment Ltd.

Wilcox, P., Lowe, M., and Cawley, P. (2001). The Effect of Dispersion on Long Range Inspection Using Ultrasonic Guided Waves. *NDT & E International*. 34, 1-9.

Williams, R.A., and Beck, M.S. (1995). *Process Tomography - Principles, Techniques and Application.* Oxford: Butterworth- Heinemann.

Wold, K., and Sirnes, G. (2007). FSM Technology: 16 Years of Field History Experience, Status and Further Developments, *NACE Corrosion.*

Wright W. M. D., and O'Sullivan I. J (2003). Ultrasonic Tomographic Imaging of Air Flow in Pipes Using An Electrostatic Transducer Array. *Review of Quantitative Nondestructive Evaluation,* 22, 666-673. American Institute of Physics.

Xu, L., Han, Y., Xu, L.A., and Yang, J. (1997). Application of Ultrasonic Tomography to monitoring gas/liquid flow. *Chemical Engineering Science*, Vol.52. No.13, pp. 2171-2183.

Yang, M., Schlaberg, H.I., Hoyle, B.S., Beck, M.S., and Lenn, C. (1999). Real-time Ultrasound Process Tomography for Two-phase Flow Imaging using a Reduced Number of Transducers. *IEEE Transactions on Ultrasonic, Ferroelectrics and Frequency Control*. 46.

Yang, W., and Peng, L. (2003). Image Reconstruction Algorithm for Electrical Capacitance Tomography. *Measurement Science Technology, vol 14*. Pp. R1-T13.

Zakaria, Z., Fazalul Rahiman, M.H. and Abdul Rahim, R. (2010). Simulation of the Two-Phase Liquid-Gas Flow through Ultraosnic Transceivers Application in Ultrasonic Tomography. *Sensors & Transducers.* 112(1), 24-38.

Zeng, G.L. (2001). Image Reconstruction- A Tutorial. *Computerized Medical Imaging and Graphics.* 25, 97-103.

Zho, Z., Feng, Z., Gao, Y., and Bai, J. (2006). An Outline of Applications of Ultrasonic Guided Waves in Non-Destructive Testing of Large Strutures. *12th Asia-Pacific Conference on NDT.* Auckland, New Zealand.

Zhoa, Y., Lin, L., Li, X.M., and Lei, M.K. (2010). Simultaneous Determination of the Coating Thickness and Its Longitudinal Velocity by Ultrasonic Nondestructive Method. *NDT & E International.* 43, 579-585.

Zhang, S.H., Yan, Y.J., and Wu, Z.Y. (2007). Electric Potential Detection for Structural Surface Crack Using Coating Sensors. *Sensors and Actuator*. 223-229.