APPLICATION OF ULTRASONIC GUIDED WAVE FOR STRUCTURAL HEALTH MONITORING OF PIPELINE

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DEDICATION

In the name of Allah, the Most Beneficent, the Most Merciful.

“ Glory be to you, we have no knowledge except what you have taught us. Verily, it is You, the All-Knower, the All-Wise”

(Al-Baqarah: 32)

To my family,

Thank you for your prayers and support.

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ABSTRACT

Corrosion and erosion in pipes are a major concern for the chemical industries specifically during the transportation of corrosive chemicals in steel pipes.Such problems can lead to potential unscheduled plant down time and economic losses which can be in the order of USD500K per day. Conventional ultrasonic thickness (UT) measurement is routinely used to quantify remaining wall thickness of pipes. In most practical transportation pipeline situations, the test surface is so large that apoint by point inspection of the entire surface is not feasible. As a result, industries seek a more efficient method to detect defects on their pipelines. In this work, the application of guided wave technology to address this serious industrial problem was quantitatively assessed in terms of technical capabilities, economic feasibility and suitability to be incorporated as part of the industry risk based inspection programmes. The technical capabilities are qualitatively and quantitatively assessed through nine performance objectives, which were formulated to determine if it can be adopted in the industry. Through laboratory study and field work at a paint pigment chemical manufacturing plant, it was shown that guided wave successfully met all nine performance objectives. It was demonstrated to be suitable for the detection of common defects such as pit and patch corrosion in a 12 inch nominal pipe size (NPS) Schedule 60 sulphuric acid pipeline.Key performance achievements found from this field study included a maximum inspection range of 260m from a single test location and the capability of detecting and monitoring growth of defect of up to 2% cross-sectional area loss. Through the use of the Inspection Value Method, it was shown in the case of the 2.75km acid pipeline the use of guided wave with follow-up UT inspection can value their system at a net present value (NPV) of RM0.9 million at the 25th year; in comparison to NPV of - RM0.1 million (negative) as a result of using conventional manual UT on its own.A new inspection procedure which incorporates the use of guided wave along with other conventional NDT methods was proposed which complied with API 579-1 Fitness for Service requirements.

ABSTRAK

Karat dan hakisan dalam paip adalah menjadi salah satu masalah utama dalam industri petrokimia khususnya dalam pengaliran bahan kimia yang boleh menghakis paip keluli. Hakisan sedemikian boleh membawa kepada kerosakan yang tidak diduga. Kerugian pendapatan boleh mencapai sehingga USD500K sehari. Pengukuran konvensional ultrasonik (UT) kerap diguna sebagai kaedah untuk mengesan ketebalan dinding paip. Secara praktikal, paip mempunyai permukaan keseluruhan yang amat besar yang perlu di imbas yang menyebabkan ujian tidak boleh dilaksanakan. Oleh itu, industri perlu kepada kaedah yang lebih efisien untuk mengesan kecacatan pada saluran paip mereka. Dalam kerja ini, aplikasi teknologi gelombang untuk menangani masalah serius industri ini telah dinilai secara kuantitatif dari segi teknikal, kewangan dan kesesuaian untuk digabungkan sebagai sebahagian daripada program pemeriksaan berasaskan risiko dalam industri. Keupayaan teknikal dinilai secara kualitatif dan kuantitatif melalui sembilan objektif prestasi, yang dicadangkan untuk menentukan sama ada ianya boleh diguna dalam industri. Melalui kajian makmal dan tapak di sebuah kilang pembuatan cat kimia pigmen, kaedah ini telah menunjukkan bahawa teknologi gelombang ini memenuhi kesemua sembilan objektif prestasi. Ianya dibuktikan sesuai dalam pengesahan kecacatan yang biasa dihadapi iaitu lubang dan tampalan kakisan pada 12 inci untuk talian paip asid sulfurik. Pencapaian prestasi utama yang diperoleh daripada kajian tapak dengan menggunakan gelombang pelaksanaan ini termasuklah keupayaan mencapai pemeriksaan maksimum sepanjang 260m dengan keupayaan mengesan dan memantau kecacatan sehingga 2% keratan rentas. Melalui penggunaan Nilai Kaedah Pemeriksaan, dalam kes 2.75 km paip asid ini, menggabungkan kaedah teknologi gelombang yang disusuli pemeriksaan UT boleh mencapai nilai bersih kini (NPV) daripada RM0. 9 juta pada tahun ke-25; berbanding dengan NPV dari -RM0.1 juta (negatif) hasil dengan penggunaan UT sahaja. Kaedah pemeriksaan baru yang melibatkan penggunaan gelombang dengan kaedah konvensional NDT yang dicadangkan ini mematuhi keperluan API 579-1 *Fitness for- Service*.

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LIST OF ABBREVIATIONS

CSC	-	Cross-sectional Change
DAC	-	Distance Amplitude Curve
EFC	-	Enhanced Focusing Capability
EHS	-	Environmental, Health & Safety
FR	-	Frequency Regime
GUL	-	Guided Ultrasonic Limited
HTM	-	Huntsman-Tioxide Malaysia
IGSB	-	Inter-Granite Sdn. Bhd.
LRUCM	-	Long Range Ultrasonic Condition Monitoring of Engineering Assets
LRUT	-	Long Range Ultrasonic Testing
NDT	-	Non-destructive testing
PDE	-	Partial Differential Equation
PSM	-	Process Safety Management
PHMSA	-	Pipeline and Hazardous Materials Safety Administration
POD	-	Probability of Detection
RBI	-	Risk Based Inspection
SMEs	-	Small and Medium Sized Enterprises
TP	-	Test position
UT	-	Ultrasonic Thickness
WE	-	White End
WPPS	-	Wavemaker Pipe Screening System
WSE	-	Written Scheme of Examination

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CHAPTER 1

INTRODUCTION

1.1 Structural Health Monitoring of Pipeline

Structural health monitoring (SHM) refers to the process of in-line permanently installed monitoring sensors for effective management of structural systems with respect to the potential occurrence of damage. The goal of a SHM system is to decrease the cost of sustaining safe operations by facilitating condition-based maintenance. In other words, the principal objective is to direct decision-making based on the current health of the structure (Farrar & Worden, 2007). Whilst related, SHM systems are distinguished in concept from non-destructive (NDE) approaches in two major respects namely;

1. SHM systems utilise embedded sensors to provide monitoring without the need to take the system offline for inspection.
2. SHM systems are focussed on more autonomous operation, reducing or even eliminating the need for expert interpretation of results.

1.2 Guided Wave Ultrasonic Testing

Guided Wave Ultrasonic Testing (GWUT) or Long Range Ultrasonic Testing (LRUT) is one of latest methods in the field of non-destructive evaluation. The method employs mechanical stress waves that propagate along an elongated structure while guided by its boundaries. This allows the waves to travel a long distance with little loss in energy. Higher frequencies can be used in some cases, but detection range is significantly reduced. In addition, the underlying physics of guided waves is more complex than bulk waves. Much of the theoretical background has been addressed in a Section 3.

Ultrasonic testing (UT) is a family of non-destructive testing techniques based on the propagation of ultrasonic waves in the object or material tested. In most common UT applications, very short ultrasonic pulse-waves with centre frequencies ranging from 0.1-15 MHz, and occasionally up to 50 MHz, are transmitted into materials to detect internal flaws or to characterize materials. A common example is ultrasonic thickness measurement, which tests the thickness of the test object, for example, to monitor pipework corrosion. The “Time of Flight” of an ultrasonic wave is directly proportional to the thickness of the material measured. This is described in Figure 1.1.

Figure 1.1 Principles of conventional UT

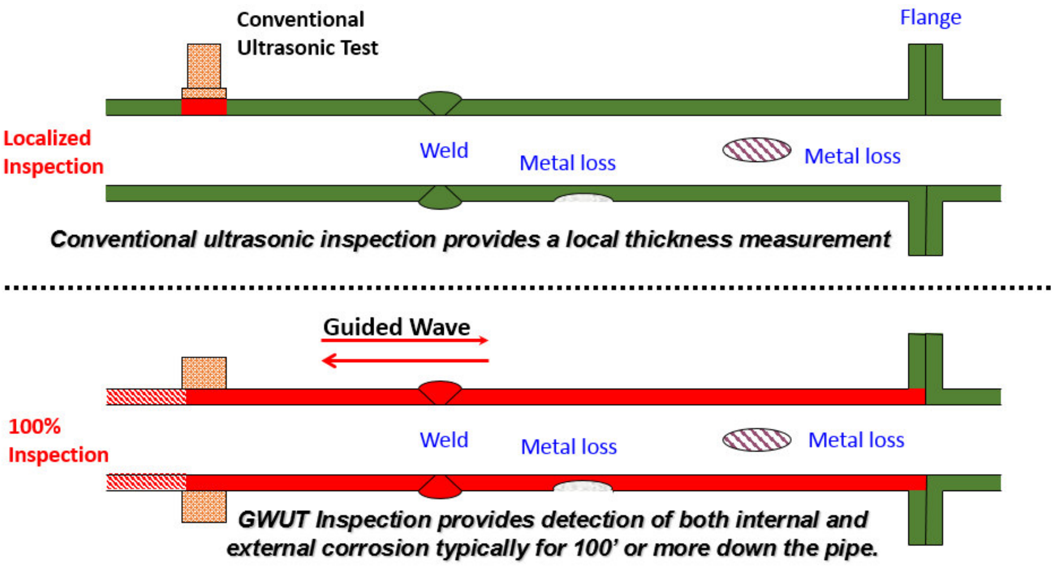

Figure 1.2 Comparison between conventional ultrasonic testing (UT) and guided wave ultrasonic testing (GWUT)

While conventional UT measures the wall thickness at a spot, advanced guided wave ultrasonic testing (GWUT) can identify locations of metal loss along a length of the pipe (Guided Ultrasonics, 2010).

Some of the differences between conventional ultrasonic waves and guided waves (see Figure 1.2) are;

1. Guided waves are mechanical stress waves that travel along the wall of the pipe; therefore the entire volume of the pipe is inspected,
2. Frequencies used in guided wave inspection are much lower than conventional ultrasonic testing; therefore the wave lengths are much longer and are scattered instead of reflected from changes in the dimension of the wave guide; typically between 30 – 75 KHz,
3. The pipe acts as a wave guide, permitting the waves to travel long distances,
4. The waves can be introduced at a single location into the pipe by one of two systems and these are;

a) An array of piezoelectric crystals are positioned in modules that typically hold two transducers each. The modules are spaced around the pipe under an air bladder which when pressurized forces the units against the surface. The individual crystals oscillate at the frequency at which they are excited and transmit the wave into the pipe.

b) Coils of insulated wire are wrapped around the pipe. An alternating current is passed through the coils, and an oscillating magnetic field is produced. Due to the magnetostrictive effect of ferromagnetic materials, this produces a wave in the pipe which can be amplified by using a nickel or cobalt strip bonded to the pipe under the coil.

(a) (b)

Figure 1.3 (a) Piezo electric crystals transducers (b) Magnetostrictive transducers

1.3 Background Problem and Motivation

Corrosion and erosion in pipes are a major concern within the chemical industry specifically during the transportation of corrosive chemicals in steel pipes, as it could lead to potential explosions or unscheduled plant down time. Both economical and safety incentives drive the chemical industry to assess the health of pipes which could lead to either down time or disasters.

For example, oil production from Alaska's Prudhoe Bay field was reduced by 95% (of its daily production of 630,000 barrels of oil) after a leak was discovered in the Trans-Alaska Pipeline resulted in an increased in crude oil prices by over 2% (to nearly USD90). British Petroleum (BP) suffered major losses which saw their share value dipping by 2.5% at the FTSE 100 stock exchange in London (The Guardian, 2011).

In another example, the death toll from two huge blasts caused by leaked oil from a ruptured pipeline in an eastern Chinese port city (Qingdao, China) had taken 62 lives with 150 injured and contaminated approximately 3,000 square feet of the city. The pipeline owned by China's largest oil refiner, Sinopec, ruptured and leaked for about 15 minutes onto a street and into the sea before it was shut off. Hours later, as workers cleaned up the spill, the oil caught fire and exploded in two locations. This incident was classified as one of the country's worst industrial accidents of the year.

(a) Trans-Alaskan oil pipeline leak (The Guardian, 2011)

(b) Qingdao city oil pipeline leak (The Telegraph, 2013)

Figure 1.4 Examples of oil pipeline leakage accidents which had caused the loss of human lives, environmental contamination and major financial loss

Figure 1.5 Sulphuric acid pipeline structural failure near Tiger Bay, Teluk Kalong, at Huntsman Tioxide Malaysia

A further example of a major pipeline failure occurred locally at Huntsman Tioxide Malaysia (HTM) located at Teluk Kalong, Terengganu. The pipeline transports concentrated sulphuric acid to the plant and a major accident occurred when a leak and pipe structural failure occurred at a stretch of the pipeline location as shown in Figure 1.5. Although no injuries or fatalities were recorded but the incident had tarnished the good reputation held by HTM over the past 20 years. A suitable sulphuric acid pipeline integrity management system (PIMS) which complies with industry standards is required to be implemented and this is the motivation of this work.

As a result, the gas, refinery, chemical and petro-chemical industries seek to detect damage to their pipeline systems at the earliest possible time. In order to do this, it would require a form of structural health monitoring (SHM) system to be implemented. Guided wave ultrasonic testing (GWUT) or long range ultrasonic testing (LRUT) which is a new technology recently developed showed great potential to address these issues and has been identified to be a possible inspection tool to perform structural health monitoring (SHM) of pipelines carrying hazardous fluids.

Corrosion had been identified as one of the major factors which had caused the pipelines to leak and in this work, the application of guided ultrasonic wave for SHM of pipeline will be demonstrated in detail in both laboratory and field work.

The complexity of the corrosion profiles encountered in practice makes more challenging the sizing of these discontinuities with guided ultrasonic waves. In the literature many scientists and engineers have recognised similarities in the forms the corrosion manifested in practice. These types of discontinuities can be classified in specific groups by similarity of the mechanism of attack (Scoot, 1994) or appearance of the corroded metal (Greene, 1967). Other authors have discussed the more typical forms of corrosion related to specific metals and alloys (Uhlig, 1963) and (Evans U. R., 1960). However, as with any classification system, the classification of these corrosion types is not distinct or all-inclusive since more than one mode of attack may occur.

Conventional methods for corrosion inspections and detection exist, typically using ultrasonic and acoustics emission methods. There are however severe limitations when the pipes or components to be tested are in extreme hazardous environment, rendering such inspections feasible only during plant shutdowns. Such inspections are done at discrete and localised locations which imply that such assessment of the entire pipeline to a “hit or miss” affair, or extremely time consuming if the inspections are extended along the entire pipe line. For example, inspection of insulated pipework by spot removal poses problems such as break in weather proofing and creating a potential entry point for future water ingress (Horrocks, et al., 2010). Screening range using this method is also very little which would give rise to the potential to miss sections with defect. Moreover, inaccessibility of inspectors to carry out inspection also poses as a problem for conventional UT methods for wall thickness inspection. Buried pipes under roads and rail crossings will disable operators from inspection using conventional methods unless expensive excavation work is carried out to expose the buried pipes. In addition, there may not necessarily be enough space clearance to carry out these tests such as radiography or UT in areas such as pipe racks or process pipes.

Devices known as maintenance pigs and smart pigs are currently being implemented by being passed through a pipeline to measure wall thickness loss and other structural anomalies. In addition, leak indicating pressure testing and excavation to expose the surface of buried pipes for visual inspection are also used. However, these techniques are invasive and not very effective if there are internal obstructions, external dikes, or other complex geometric features along the pipeline. Furthermore, these approaches do not provide sufficient information to predict the future health of the piping unless a failure leading to leakage has already occurred. In addition, these conventional techniques are time-based inspection methods which does not offer a solution of monitoring the health of the structure at all times, which could lead to missing of a serious defect between inspection periods.

Long range ultrasonic testing (LRUT) is an advanced non-destructive testing (NDT) technology utilising guided ultrasonic wave. It is currently being implemented to overcome the limitation of conventional methods by being able to screen structures over a range of up to 100m from a single test location (Guided-Ultrasonics Ltd, 2014). In addition, this technology can be implemented for pipeline monitoring since the equipment can be retrofitted and permanently mounted onto pipes to continuously monitor the health of pipes. This technology has been developed and commercialised by a number of companies in the UK and US and it is now included in the API 570 procedures as a new pipeline safety inspection tool. Guided ultrasonic wave is a novel and promising technique which could offer a safe and economically feasible solution for the industry to detect and monitor defects on existing structures until the point is reached when they are deemed to be unsafe. However, since this technology is new in Malaysia (and also other Asian countries), the capability of the technology would therefore need to be demonstrated and validated under field condition before local plant managers are convinced of possible implementation in the industry.

1.4 Importance of the Study

Ageing of plant is commonly misunderstood as being how old an equipment is. However, its correct association should be about plant equipment condition and determining the extent of material deterioration and damage, which is usually but not necessarily associated with time in service.

The typical ageing plant damage mechanism such as erosion and corrosion then contributes to an increase in likelihood of equipment failure over the plant lifetime. Studies from the EU Major Accident Database have shown that ageing has a 50% contribution factor to technical integrity failure, which is the main factor (60%) leading to major hazard loss of containment incident (Horrocks, et al., 2010). See Table 1.1.

Table 1.1 : Average annual consequences of significant corrosion incidents between 1988 and 2007 (Horrocks, et al., 2010).

Type of Pipeline	Length (Thousands of miles)		No of Significant Incidents	Fatalities	Injuries	Property Damage (USD)
	1988	2007				
Hazardous Liquid	153	166				
Onshore			33	0.05	0.8	14
Offshore			0.9	0	0	1.7
Gas Transmission						
Onshore	284	294	7.7	0.6	0.2	8.2
Offshore	7	7	4.4	0	0	1.2
Gas Gathering	32	20	2.7	0	0.2	1.2
Gas Distribution	802	1172	3.4	0.8	3.9	0.6
Total	**1278**	**1659**	**52.1**	**1.45**	**5.1**	**26.9**

Corrosion and erosion induced pipe failures can either be pipe rupture or leaks, with the latter being more common. As seen in Figure 1.6, excavation damage and corrosion has been reported to be responsible for 1550 and 1073 significant incidents respectively in both onshore and offshore US transmission pipelines, from the period of 1988 through to 2008 (Baker, 2008). The US Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) defines an incident as significant if it causes fatality, an injury requiring hospitalisation, cost of USD50K or more, release of 5 barrels or more of a highly volatile liquid, 50 barrels or more of other liquids, or release of a liquid resulting in an unintentional fire or explosion (Baker, 2008).

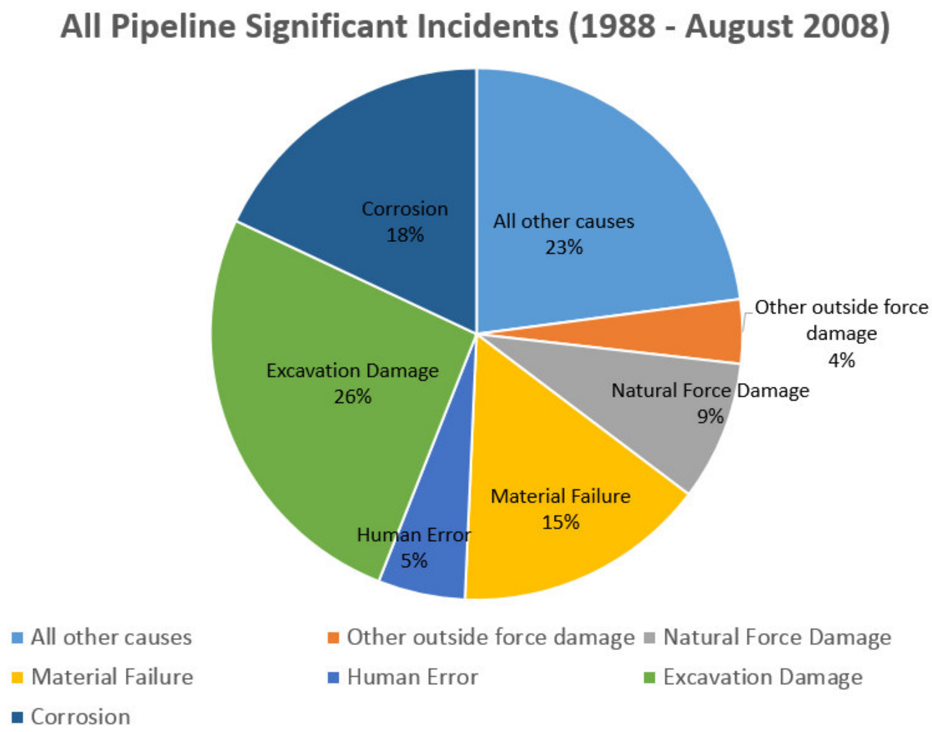

Figure 1.6 Causes of 5960 significant incidents in onshore and offshore pipelines as adapted from (Baker, 2008)

On average there have been 52 significant incidents on US pipelines per year caused by corrosion alone. These corrosion induced incidents involved onshore hazardous liquid pipelines (63%), onshore gas transmission pipelines (15%), offshore gas transmission pipelines, natural gas distribution lines, gas gathering lines and off shore liquid lines (remaining %), as shown Figure 1.6. From Figure 1.7, the pattern has been reported to be relatively consistent over time as a result of the industry's effectiveness at corrosion control.

However, the cost attributed to corrosion incidents alone is still very large and significant, with an average value of USD27 million per year for just US pipeline transmission. NACE International estimates the total costs attributed to all types of corrosion across the entire industry in the world is ata loss of USD276 billion from 1988 to 2007, which accounts for pipeline rehabilitation and replacement costs. During the same 20 year period, the 1073 corrosion induced significant incidents (or 18%) lead to 30 fatalities, 100 injuries and a total loss of assets amounting to USD551 million.

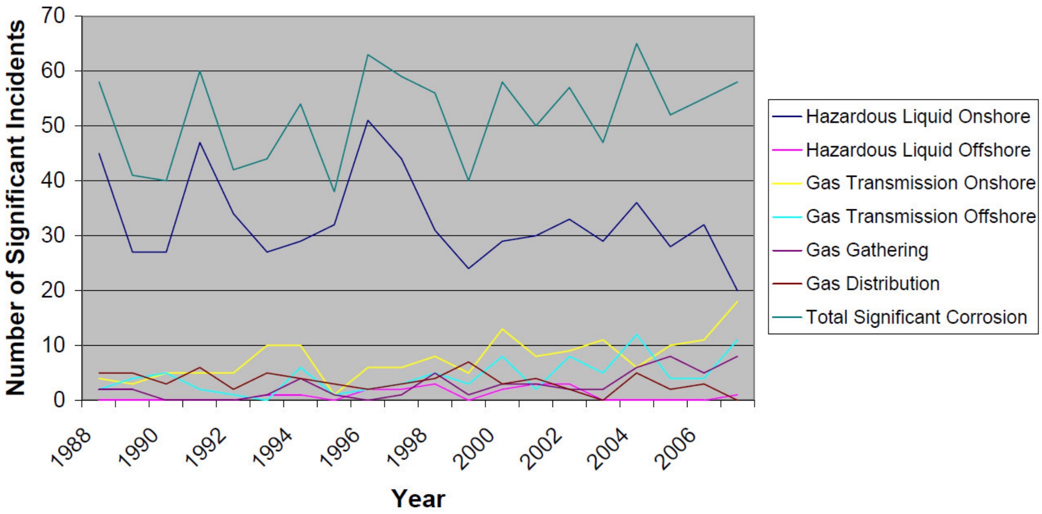

Figure 1.7 History of significant corrosion incidents in the US, extracted from (Baker, 2008)

1.5 Problem Statements

Lessons should be learnt from the fatal explosion that occurred in August 6, 2012 at Chevron Richmond refinery (California, USA) which was caused by gas leakage from a 1.5m length of 8-inch carbon steel atmospheric gas-oil pipeline. Chevron process safety management & operational excellence centre released an investigation report on April 12, 2013 stating that the cause of the pipe leak was the result of wall thinning due to sulphide corrosion. On August 2, 2013, the mayor of Richmond filed lawsuit on Chevron seeking compensation for “the legal harm to the general public as well as to the assets and resources of the city of Richmond", which is still an on-going case at the time of writing of this thesis. See Figure 1.8 and Figure 1.9. This case study was adopted by HTM as their "accident case reference".

Huntsman process safety management group (PSM) had identified this problem as "very severe" and had recommended that a condition based pipeline monitoring system to be implemented in their Tioxide plant especially in all pipes that carry sulphuric acid.

Figure 1.8 Explosion and fire caused by leakage in a 1.5m 8-inch carbon steel pipe suffering from sulphide corrosion – HTM PSM Case Reference

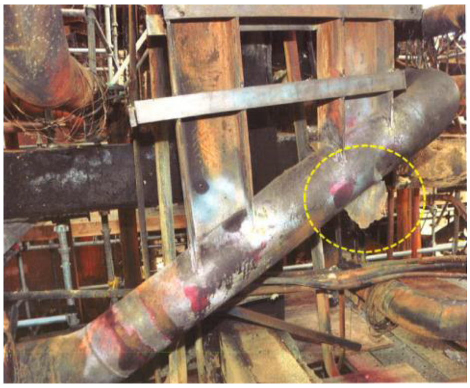

Figure 1.9 Evidence of sulfidation corrosion in the ruptured pipe

(a)

(b)

Figure 1.10 Typical sulphuric pipeline installed at HTM a) over ground pipeline b) inside containment (or buried pipe)

Corrosion and erosion of sulphuric acid pipelines causing non-uniform wall thinning are the major problems at Huntsman Tioxide Malaysia. This phenomenon occurred more severely at pipe bends (see Figure 1.10a) than at the straight pipes (see Figure 1.10b).

Current conventional sulphuric acid pipeline inspection program practiced by HTM includes visual and UT thickness measurement inspection. Inspections are done annually and the spot thickness checks are determined by qualified third party independent NDT companies. In hazardous locations, inspections can only be performed when the plant has been shut down and in “difficult to access” or non-accessible locations inspections cannot be done.

1.6 Research Objectives

There are primarily two major objectives in this Doctorate of Engineering programme and they are classified under (1) industrial and, (2) academic requirements.

1.6.1 Industrial Objectives

In this research work, there are two main industrial objectives and they are;

(1) To quantitatively assess the technical capabilities of guided wave as an inspection tool for the purpose of pipeline screening and structural health monitoring of sulphuric acid pipelines.

(2) To economically assess and quantify the cost of inspection and monitoring using guided waves.

The measurement of success in the achievement of the first objective was discussed and agreed amongst Huntsman-Tioxide Malaysia (HTM) corporate process safety management (PSM), Imperial College, London (ICL) and Universiti Teknologi Malaysia (UTM). The agreed scope of work shall comply with API 570:1998 – Piping Inspection Code and are defined as follows;

(a) To assess the feasibility of detection of erosion and hydrogen induced defects at bends and straight pipes,
(b) To establish the performance objectives of the guided wave pipe inspection tool,
(c) To quantify the performance of the inspection tool under laboratory condition and,
(d) To quantify the performance of the inspection tool under plant condition.

1.6.2 Academic Objective

Based on the definition of UTM's Engineering Doctorate (Engineering Business Management) program published in 5-April 2013, "the research work must demonstrate innovation in the application of knowledge to solve a significant industrial problem. The work should make a significant contribution to the performance of the company".

1.7 Scope and Limitations of the Study

The intent of this work was to demonstrate practical and economically feasible industrial applications of GWUT technology in SHM of pipelines. An extensive literature review of the principles and applications of guided wave technology was carried out, covering the period of 1991 to 2014.

The commercially available equipment used for the purpose of demonstration was GUL's Wavemaker™ G4mini, which was introduced into the market in early 2014. Before demonstrating the technology at the field, a pipe test rig was fabricated in the laboratory to verify the performance of this equipment at defect detection. Using the deployable solid enhanced focusing capability (EFC) ring, baseline signals were successfully established for the 9m 4” pipe loop and two test locations (above and below ground) on the 2.75km 12” sulphuric acid pipeline at Huntsman-Tioxide pigment production plant.

Due to time restriction, implementation of the more suitable gPIMS™ permanently installed ring, which is designed to be permanently installed onto the pipe (to give more stable readings for repeated monitoring) could not be carried out for this pipe section. Based on the data collected from this site, a procedure specific for these pipe sections was successfully devised for future implementation by Huntsman-Tioxide.

A preliminary economic analysis for the plant wide implementation of guided wave for the purpose of SHM was also investigated upon.

1.8 Structure of this Dissertation

This dissertation is divided into nine chapters. Chapter 1 introduces the effect of problems associated with corrosion in which the chemical industry faces. These problems includes billions of dollars’ worth of cost every year, produces about 50 fatality globally each year and damages to the environment.

Chapter 2 provides an extensive literature review of the commercial available ultrasonic guided waves products in the market. The history of the technological development of these products is briefly covered here. The current usage capabilities and limitations of these equipment and feasibility for screening pipes successfully are discussed in great details in this chapter. In addition, this chapter covers the proposed future technological improvements on ultrasonic guided wave equipment which are currently undergoing research and development.

Chapter 3 provides the background theory to ultrasonic guided waves propagating in structures. Shear horizontal (SH) waves in plates and torsional guided waves in pipes are emphasised in this thesis due to relevance to thesis. The analogy between the propagation of guided waves in pipes and plates is also presented. In addition, the choice of mode, frequency range and a general procedure to conduct finite element simulations are discussed in this chapter.

Chapter 4 outlines the methodology of this research work. It identifies the industrial problem and reviews the current industrial best practice for pipeline inspection systems. A thorough research of new NDT innovations available commercially in the market is discussed and the selection of guided wave testing (GWT) which is an advanced NDT technology is decided based upon its excellent defect detection capability. Rigorous training of the GW technology by Guided Ultrasonics Ltd. to familiarise with the technology acquired was done in order for the instrument to be applied at both laboratory level and pilot study at the industrial plant.

Chapter 5 describes the industrial case study which was done at Huntsman Tioxide, Malaysia to demonstrate the capability of GWT as a pipe screening instrument with 100% wall coverage. A list of GW performance targets including its success criteria was set by Hunstman as the objectives for the case study. The outcome of the case study was very favourable and demonstrated that GW technology was successful in meeting all the performance targets set.

Chapter 6 proposes a new pipe inspection procedure which combines the current conventional NDT with advanced NDT methods to offer an improved defect detection system to Huntsman's pipe integrity management system. In this chapter, the probability of detection (POD) of a defect in both NDT methods are discussed in detail and the benefit of combining the two methods are described.

Chapter 7 assesses the cost implications in the implementation of this new pipe inspection procedure in the plant's pipeline integrity management system. It not only shows how the improved defect detection system can prevent accidents from occurring but also saves unnecessary cost to plant operators since only the section of pipes screened with defects need to be followed up with manual UT inspection. If the pipeline has few defects, it could save plant operators more than 50% of the existing pipe inspection cost.

Chapter 8 details out the proposed general preliminary structural health monitoring procedure for the transportation pipes involved in HTM's process flow.

Chapter 9 summarises the key findings and contribution of this work along with recommendation for future works.

REFERENCES

A. Demma, D. A. (2011). Inspection of Pipes using Guided Waves : state of the art. *5th Pan American Conference for NDT*. Mexico.

Abaqus. (2010). *User Manual Version 6.9*. Retrieved from www.simulia.com

Alleyne, D. a. (1992a). Optimisation of Lamb wave inspection techniques. *NDT&E International, Vol 25, pp11-22.*

Alleyne, D. a. (1992b). The interaction of Lamb waves with defects. *IEEE Trans UFFC, Vol 39, pp381-397.*

Alleyne, D. a. (1996a). The excitation of Lamb waves in pipes using dry coupled piezoelectric transducers. *J NDE, Vol 15, pp11-20.*

Alleyne, D. a. (1997). Long range propagation of Lamb waves in chemical plant pipework. *Materials Evaluation, Vol 55, pp504-508.*

Alleyne, D. C. (1997). The Lamb Wave Inspection of Chemical Plant Pipework. *Review of Progress in Quantitative NDE, Vol 16, DO Thompson and DE Chimenti (eds), Plenum Press, New York, pp1269-1276.*

Alleyne, D. L. (1998). The reflection of guided waves from circumferential notches in pipes. *ASME J Applied Mechanics, Vol 65, pp635-641.*

Alleyne, D. N., & Cawley, P. (1992). The interaction of lamb waves with defects. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency control, 39(3):381*.

Alleyne, D. P. (2001). Rapid, long range inspection of chemical plant pipework using guided waves. *Insight, Vol 43, pp93-96.*

Alleyne, D., & Cawley, P. (1991). A two-dimensional fourier transform method for the measurement of propagating multimode signals. *Journal of Acoustical Society of America, 89*(3), 1168.

Alleyne, D., & Cawley, P. (1996a). The excitation of Lamb waves in pipes using dry coupled piezoelectric transducers. *J NDE, Vol 15, pp11-20.*

Alleyne, D., & Cawley, P. T. (1996b). The effect of discontinuities on the long range propagation of Lamb waves in pipes. *Proc I Mech E, Part E: J Process mech Eng, Vol 210, pp217-226.*

Anon. (1999). Guide on methods for assessing the acceptability of flaws in fusion welded structures. *BS 7910 : 1999, Incorporating Amendment No. 1, British Standards Institution, London, UK*.

Anon. (2001). Managing System Integrity for Hazardous Liquid Pipelines. *API Standard 1160 (ANSI/API STD 1160-2001), First Edition, November*.

API 570. (1998). Piping Inspection Code. *American Petroleum Institute, 2nd edition*.

API 579-1, A. P. (2007). *API 579-1: Fitness for service.*

API 579-1/ASME FFS-1. (2007). *Fitness-for-service* .

ASME B31.4. (1999). *Pipeline transportation systems for liquid and hydrocarbonss and other liquids.* (1998 ed.). New York.

ASTM-E2775-11. (2011). *Standard Practice for Guided Wave Testing of Above Ground Steel Pipework Using Piezoelectric Effect Transduction.* ASTM.

ASTM-E2929-13. (2013). *Standard Practice for Guided Wave Testing of Above Ground Steel Piping with Magnetostrictive Transduction.* ASTM.

Auld, B. (1990). *Acoustic fields and waves in solids.* Kreiger, Malabar, Florida.

Bai, H. S. (2001). Scattering of guided waves by circumferential cracks in steel pipes. *ASME J Applied Mechanics, Vol 68, pp619-631.*

Baker, M. (2008). *Pipeline Corrosion.* U.S. Department of Transportation Pipeline and Hazardous Material Safety Administration Office of Pipeline Safety.

Beard, M. L. (2002). Development of a guided wave inspection technique for rock bolts. *Insight, Vol 44, pp19-24.*

Beard, M. L. (2003a). Ultrasonic guided waves for inspection of grouted tendons and bolts. *ASCE J Materials in Civil Engineering, Vol 15, pp212-218.*

Beard, M. L. (2003b). Non-destructive testing of rock bolts using guided ultrasonic waves. *Int J Rock Mech & Mining Sci, Vol 40, pp527-536.*

Beaumont, M. R. (2006). Mechanical Integrity Best Practice for Sulphuric Acid Plants. Loss prevention symposium.

Böttger, W. S. (1987). Prototype EMAT system for tube inspection with guided ultrasonic waves. *Nuclear Eng. and Design, Vol 102, pp356-376.*

Brotton, J. (2002). *Corrosion at pipe supports: Causes and solutions.* Technical report, Deepwater Corrosion Services.

BS9690. (2011). *Non-destructive testing – Guided wave testing – Part 1: General principles.* BSI.

BS9690. (2011). *Non-destructive testing – Guided wave testing – Part 2: Basic requirements for guided wave testing of pipes, pipelines and structural tubulars.* BSI.

BS9690. (2011). *Non-destructive testing – Guided wave testing – Part 2: Basic requirements for guided wave testing of pipes, pipelines and structural tubulars.* BSI.

Caradente, R., & Cawley, P. (2011). *Interaction between the fundamental torsional guided wave mode and complex defects in pipe.* London: Imperial College London.

Carandente, R. (2012). *Interaction between the fundamental torsional guided wave mode and complex defects in pipes.* Imperial College PhD thesis.

Castaings, M. L. (2002). Modal decomposition method for modelling the interaction of Lamb waves with cracks. *J Acoust Soc Am, Vol 112, pp2567-2582.*

Cawley, P. A. (1994). Inspection of pipes. *WO 96/12951, priority date 20-10-1994.*

Cawley, P. L. (2003). Practical long range guided wave inspection - applications to pipes and rail. *Materials Evaluation, Vol 61, pp66-74.*

Cawley, P., Cegla, F., & Stone, M. (2012). Corrosion monitoring strategies-Choice between area and point measurements. *J NonDestructive Evaluation*(DOI 10.1007/s10921-012-0168-2).

Cho, Y. a. (1996). A boundary element solution for a mode conversion study on the edge reflection of Lamb waves. *J Acoust Soc Am, Vol 99, pp2097-2109.*

Cho, Y. H. (1997). Lamb wave scattering analysis for reflector characterization. *IEEE Trans UFFC, Vol 44, pp44-52.*

Clarke, T. (2009). *Guided Wave Health Monitoring Of Complex Structures.*

Clarke, T., Simonetti, F., & Cawley, P. (2010). Guided wave health monitoring of complex structures by sparse array systems: influence of temperature changes on performance. *Journal of Sound and Vibration.*

Cosham, A., & Hopkins, P. (2004). The assessment of corrosion in pipelines – guidance in the pipeline. Amsterdam.

Cosham, A., & Hopkins, P. (2004). The assessment of corrosion in pipelines – guidance in the pipeline defect assessment manual (PDAM). Amsterdam, The

Netherlands: Pipeline Pigging and Integrity Management Conference 17-18th May.

Daryl Corbin, E. W. (2007). New Technology for Real-Time Corrosion Monitoring. *TRI-SERVICE Corrosion Conference.*

Datta, S. S. (1982). Diffraction of medium and long wavelength horizontally polarized shear waves by edge cracks. *J Appl Phys, Vol 53, pp2895-2903.*

Daud, M. A. (2011). *Report of Examination of Piping.* Axiom Engineering Associates Ltd.

Daud, M. A. (2011). *Report of Examination of Piping.* Axiom Engineering Associates Ltd.

Davies, J. (2000). *Corrosion: Understanding the basics.* ASM International.

Davies, J. O. (2008). *Inspection of Pipes using Low Frequency Focused Guided Wave.* London: Imperial College London.

Davies, J. R. (2000). *Corrosion: Understanding the basics.* ASM International.

Davies, J. S. (2006). Review of Synthetically Focused Guided Wave Imaging Techniques with Application to Defect Sizing. *Review of Progress in Quantitative NDE, Vol 25, DO Thompson and DE Chimenti (eds), American Institute of Physics, in press.*

Demma, A. A. (2003c). Testing offshore risers using guided waves. *internal report, Guided Ultrasonics Ltd..*

Demma, A. C. (2003a). Scattering of the fundamental shear horizontal mode from steps and notches in plates. *J Acoust Soc Am, Vol 113, pp1880-1891.*

Demma, A. C. (2003b). The reflection of the fundamental torsional mode from cracks and notches in pipes . *J Acoust Soc Am, Vol 114, pp611-625.*

Demma, A. C. (2004). The reflection of guided waves from notches in pipes: a guide for interpreting corrosion measurements. *NDT&E International, Vol 37, pp167-180.*

Demma, A. C. (2004). The reflection of guided waves from notches in pipes: a guide for interpreting corrosion measurements. *NDT&E International, Vol 37, pp167-180.*

Demma, A. C. (2005). The effect of bends on the propagation of guided waves in pipes. *Trans ASME J Pressure Vessel Technology, Vol 127, pp328-335.*

Demma, A. C. (2005). The effect of bends on the propagation of guided waves in pipes. *Trans ASME J Pressure Vessel Technology, Vol 127, pp328-335.*

Diligent, O. a. (2005). Reflection of the S0 Lamb mode from a flat bottom circular hole. *J Acoust Soc Am, Vol 118, pp2869-2879.*

Diligent, O. G. (2002). The low frequency reflection and scattering of the S0 Lamb mode from a circular through-thickness hole in a plate: Finite Element, analytical and experimental studies. *J Acoust Soc Am, Vol 112, pp2589-2601.*

Ditri, J. (1996). Some results on the scattering of guided elastic SH waves from material and geometric waveguide discontinuities. *J Acoust Soc Am, Vol 100, pp3078-3087.*

Doosan Babcock Energy Limited. (2009). *Evaluation of the effectiveness of non-destructive testing screening methods for in-service inspection.* Health and Safety Executive.

Edwards, G. (2006). *Long Range Ultrasonic Testing – New Markets for New Technology.* Long Range Ultrasonic Condition Monitoring of Engineering Assets (Coll-CT-2005-516405).

Edwards, G. (2006). New Markets for New Technology - Long Range Ultrasonics Testing. *LRUCM Consortium.* TWI Ltd.

Engelhardt, G., & Macdonald, D. (1998). Deterministic prediction of pit depth distribution. *Journal of Corrosion NACA*, 469-479.

Evans, M., & Vogt, T. (2010). *Reliability of guided wave testing.* ENDT.

Evans, M., & Vogt, T. (2010). Reliability of guided wave ultrasonic testing. *ECNDT - Moscow*.

Evans, U. R. (1960). *The corrosion and oxidation of metals.* Edward Arnold Ltd.

Farrar, C., & Worden, K. (2007). *An introduction to structural health monitoring.* Sheffield: Philosophical Transaction ofthe Royal Society.

Fitch, A. (1963). Observation of elastic-pulse propagation in axially symmetric and non-axially symmetric longitudinal modes of hollow cylinders. *Journal of the Acoustical Society of America, 35*(5), 706-708.

Fortunko, C. K. (1982). Nondestructive evaluation of planar defects in plates using low frequency SH waves. *J Appl Phys, Vol 53, pp3450-3458.*

Fromme, P. W. (2005). A guided ultrasonic wave array for structural integrity monitoring. *Review of Progress in Quantitative NDE, Vol 24, DO Thompson and DE Chimenti (eds), American Institute of Physics, pp1780-1787.*

Galbraith, J. M., & Williamson, G. C. (2008). *Practical considerations for users of guided wave ultrasonic testing.* NACE International, 07164.

Galbraith, J. M., & Williamson., G. C. (2008). Practical considerations for users of guided wave ultrasonic testing. *NACE International, 07164*.

Galvagni, A. (2013). *Pipeline Health Monitoring.*

Galvagni, A. (2013). *Pipeline Health Monitoring.* Imperial College London PhD Thesis.

Gazis, D. (1959). Three dimensional investigation of propagation of waves in hollow circular cylinders. *Journal of the Acoustical Society of America, 31*(5), 568-578.

Grahn, T. (2003). Lamb wave scattering from a circular partly through-thickness hole in a plate. *Wave Motion, Vol 37, pp63–80.*

Greene, M. G. (1967). *Corrosion Engineering.* McGraw Hill.

Gridin, D. C. (2003). The high-frequency asymptotic analysis of guided waves in a circular elastic annulus. *Wave Motion, Vol 38, pp67-90.*

Grills, R. H. (2001). *Probability of Detection - A NDT Solution.* Retrieved from http://www.asnt.org/publications/materialseval/solution/jul01solution/.

Guided Ultrasonics Ltd. (2007). *Wavemaker G3 Procedure based Training Manual.*

Guided Ultrasonics, L. (2010). *GUL 105: 2010 Standard Practice for the GWT of Basic Pipe-work using the Wavemaker G3 Pipe Screening System* (2 ed.). Nottingham.

Guided-Ultrasonics Ltd. (2014). Retrieved from Guided-Ultrasonics Ltd: http://www.guided-ultrasonics.com

GUL, G. U. (2013). *gPIMS Sensors*. Retrieved from http://www.guided-ultrasonics.com/public2013/?page_id=922.

Haddara, F. I. (2003). Risk-based maintenance (rbm): a quantitative approach. *J. Loss Prevent. Proc.,.*

Hardy, F. (2009). *Evaluation of the effectiveness of non-destructive testing screening methods for in-service inspection.*

Hassan, W. a. (1997). Circumferential creeping waves around a fluid-filled cylindrical cavity in an elastic medium. *J Acoust Soc Am, Vol 101, pp2496-2503.*

Hayashi, T. a. (2002). Multiple reflections of Lamb waves at a delamination. *Ultrasonics, Vol 40, pp193-197.*

Hayashi, T. a. (2005). Defect imaging with guided waves in a pipe. *J Acoust Soc Am, Vol 117, pp2134-2140.*

Hayashi, T. K. (2003). Analysis of flexural mode focusing by a semianalytical finite element method. *J Acoust Soc Am, Vol 113, pp1241-1248.*

Haynes, C. M. (2014). *Effective Health Monitoring Strategies for Complex Structures.* University of Calfornia, San Diego.

Hopkins, P. (2001a). Pipeline integrity-training our engineers and what they need to know. Mexico.

Hopkins, P. (2001b). Pipeline integrity reviews. Houston: Clarion Press.

Horrocks, P., Mansfield, D., Parker, K., Thompson, J., Atkinson, T., & Worsley, J. (2010). *Managing Ageing Plant.* Health & Safety Executives (HSE) Books.

HSE. (2012). *Failure rate and event data for use within risk assessments.* Retrieved October 7, 2014, from www.hse.gov.uk/landuseplanning/failure-rates.pdf

http://www.guided-ultrasonics.com. (2011, 07 09). Retrieved 07 09, 2011

Huntsman. (2010). *Sustainability Report : We See A Better World.*

Hutchins, D. J. (1993). Lamb Wave Tomography using noncontact transduction. *Ultrasonics, Vol 31, pp97-103.*

Ideris, E., & Yahya, M. F. (2010). *12" Acid Sulphuric Pipeline-12-R17-031-II (01)-Visual and UTTM Inspection Report.* Malaysia: TestEx (M) Sdn Bhd.

K. Worden, C. R. (2007). The fundamental axioms of structural health monitoring. *Proc. R. Soc. A, vol. 463, p. 1639.*

Kiefner, J. F., & Leewis, K. (2011). *Pipeline Defect Assessment - A Review & Comparison of Commonly Used Methods.* Report No. L52314.

King, R. a. (1982). Extended variational solution for scattering from flaws in plates. *J Appl Phys, Vol 53, pp3459-3460.*

Koshiba, M. H. (1987). Finite Element solution of horizontally polarized shear wave scattering in an elastic plate. *IEEE Trans UFFC, Vol 34, pp461-466.*

Koshiba, M. K. (1984). Finite Element analysis of Lamb wave scattering in an elastic plate waveguide. *IEEE Trans Son Ultrason, Vol SU-31, pp18-25.*

Kwun, H. a. (1995). Feasibility of under-lagging corrosion detection in steel pipe using the magnetostrictive sensor technique. *NDT&E International, Vol 28, pp211-214.*

Kwun, H. a. (1995). Feasibility of under-lagging corrosion detection in steel pipe using the magnetostrictive sensor technique. *NDT&E International, Vol 28, pp211-214.*

Kwun, H. K. (2003). The magnetostrictive sensor technology for long range guided wave testing and monitoring of structures. *Materials Evaluation, Vol 61, pp80-84.*

Le Clezio, E. C. (2002). The interaction of the S0 Lamb mode with vertical cracks in an aluminium plate. *Ultrasonics, Vol 40, pp187-192.*

Lewis, K. (2001). Integrity Management of Pipelines. *Congreso Internacional de Ductos (International Pipeline Congress), Mérida, Yucatán, Mexico, 14-16 November*.

Li, J. (2005). On circumferential disposition of pipe defects by long range ultrasonic guided waves. *Trans ASME J Pressure Vessel Technology, Vol 127, pp530-537.*

Li, J. a. (2002). Angular-profile tuning of guided waves in hollow cylinders using a circumferential phased array. *IEEE Trans UFFC, Vol 49, pp1720-1729.*

Liu, G. a. (1998). Guided circumferential waves in a circular annulus. *ASME J Applied Mechanics, Vol 65, pp424-430.*

Liu, Z. H. (2006). Circumferential and longitudinal defect detection using T(0,1) mode excited by thickness shear piezoelectric elements. *Ultrasonics, Vol 44 (in press) (Presented at UI/WCU conference Beijing, Sept 2005).*

Lowe, M. (1998). Characteristics of the reflection of Lamb waves from defects in plates and pipes. *Review of Progress in Quantitative NDE, Vol 17, DO Thompson and DE Chimenti (eds), Plenum Press, New York, pp113-120.*

Lowe, M. A. (1998). The mode conversion of a guided wave by a part-circumferential notch in a pipe. *ASME J Applied Mechanics, Vol 65, pp649-656.*

Lowe, M. C.-Y. (2002b). The low frequency reflection characteristics of the fundamental antisymmetric Lamb wave a0 from a rectangular notch in a plate. *J Acoust Soc Am, Vol 112, pp2612-2622.*

Lowe, M. D. (2002a). Low frequency reflection characteristics of the S0 Lamb wave from a rectangular notch in a plate. *J Acoust Soc Am, Vol 111, pp64-74.*

Lowe, M., & Cawley, P. (2006). *Long Range Guided Wave Inspection Usage - Current Commercial Capabilities and Research Directions.* Department of Mechnical Engineering, Imperial College London.

Luo, W. R. (2004). Circumferential shear horizontal wave axial crack sizing in pipes. *Research in Nondestructive Evaluation, Vol 15, pp149-171.*

McKeon, J. a. (1999a). Lamb wave scattering from a through hole. *J Sound Vib, Vol 224, pp843-862.*

McKeon, J. a. (1999b). Parallel projection and crosshole Lamb wave contact scanning tomography. *J Acoust Soc Am, Vol 106, pp2568-2577.*

Mirsky, I. (1965). Wave propagation in transversely isotropic circular cylinders, Part 1: Theory. *Journal of the Acoustical Society of America, 37*(6), 1016-1021.

Mohr, W. a. (1976). On inspection of thin walled tubes for transverse and longitudinal flaws by guided ultrasonic waves. *IEEE Trans Sonics and Ultrasonics, Vol SU-23, pp369-374.*

Moser, F., Jacobs, L., & Qu, J. (1999). Modelling elastic wave propgation in waveguides with the finite element method. *NDT & E international, 32*, 225-234.

Mudge, P. (2001). Field application of the Teletest long range ultrasonic testing technique. *Insight, Vol 43, pp74-77.*

Mudge, P. a. (1997). Detection of corrosion in pipes and pipelines. *ASNT International Chemical and Petroleum Industry Inpection Technology Topical Conference V, Houston Texas*.

Nagy, P. B. (1994). Weep hole inspection by circumferential creeping waves. *NDT & E Int, Vol27, pp131-142.*

Nishino, H., Takashima, S., Uchida, F., Takemoto, M., & Ono, K. (2001). Modal analysis of hollow cylindrical guided waves and applications. *Japanese Journal of Applied Physics, 40*, 364-370.

Norris, A. a. (1995). Scattering of flexural waves on this plates. *J Sound Vib, Vol 181, pp115-125.*

Norris, A. a. (1997). Flexural wave propagation and scattering on thin plates using Mindlin theory. *Wave Motion, Vol 26, pp1-12.*

Ogilvy, J. A. (1993). *NDT & E International, Vol 26, No 1.*

Olympus. (2012). *http://www.olympus-ims.com/en/pipewizard/.* Retrieved August 23, 2015

Paris, P., & Erdogan, F. (n.d.). A critical analysis of crack propagation laws. *Journal of Basic Engineering (Trans. ASME) 85D (4) 528 to 534.*

Patel, R. J. (2005). Risk Based Inspection. *Middle east non-destructive testing conference.* Bahrain.

Pavlakovic, B. (1998). *Leaky guided ultrasonic waves in NDT.* London: Imperial College London.

Pavlakovic, B. L. (1997). Disperse: a general purpose program for creating dispersion curves. *Review of Progress in Quantitative NDE, Vol 16, DO Thompson and DE Chimenti (eds), Plenum Press, New York, pp185-192.*

Pavlakovic, B. L. (2001). High frequency low loss ultrasonic modes in embedded bars. *ASME J Applied Mechanics, Vol 68, pp67-75.*

PHMSA. (2007). *Guided wave UT Target items for go-no go procedures - the '18 point' guidelines.* PHMSA.

PHMSA. (2010, March 1). *Guidelines for integrity assessment of cased pipe for gas transmission pipelines in high consequence areas (HCAs), Revision 0, publ.* Retrieved from http://primis.phmsa.gov/gasimp/documents.htm

RACH. (1999). Reliability Assessment for Containment of Harzardous Materials (RACH). *European Commission Project OG 112/FR/UK, Final Report*.

Richardson, S. (2012). *Safety & Loss Prevention (Lecture Notes)* (pp. 1-12 ed.). Imperial College London.

Rokhlin, S. (1980). Diffraction of Lamb waves by a finite crack in an elastic layer. *J Acoust Soc Am, Vol 67, pp1157-1165.*

Rokhlin, S. (1981). Resonance phenomenon of Lamb waves scattering by a finite crack in a solid layer. *J Acoust Soc Am, Vol 69, pp922-928.*

Rose, J. (1999). *Ultrasonic waves in solid media.*

Rose, J. D. (1999). A guided wave inspection technique for nuclear steam generator tubing. *Cambridge University Press.*

Rose, J. L. (2004). *Ultrasonic Waves in Solid Media.* Pennsylvania: Cambridge University Press.

Rose, J. L. (2005). A natural focusing low frequency guided wave experiment for the detection of defects beyond elbows. *ASME J Pressure Vessel Technology, Vol 127, pp310-316.*

Rose, J. S. (2003). Guided wave flexural mode tuning and focusing for pipe inspection. *Materials Evaluation, Vol 61, pp162-167.*

Scoot, S. D. (1994). Corrosion in the petrochemical industry. *ASM International*.

Shin, H. a. (1998). Guided wave tuning principles for defect detection in tubing. *J NDE, Vol 17, pp27-36.*

Sicard, R. C. (2004). Guided Lamb waves and L-SAFT processing techniques for enhanced detection and imaging of corrosion defects in plates with small depth-to-wavelength ratio. *IEEE Trans UFFC, Vol 51, pp1287-1297.*

Sicard, R. G. (2002). A SAFT algorithm for Lamb wave imaging of isotropic plate-like structures. *Ultrasonics, Vol 39, pp487-494.*

Silk, M. G. (1979). The propagation in metal tubing of ultrasonic wave modes equivalent to Lamb waves. *Ultrasonics, Vol 17, pp11-19.*

Silk, M. G., & Bainton, K. F. (1979). The propagation in metal tubing of ultrasonic wave modes equivalent to Lamb waves. *Ultrasonics, Vol 17, pp11-19.*

Simonetti, F. a. (2004). On the nature of shear horizontal wave propagation in elastic plates coated with viscoelastic materials. *Proc Royal Soc Lond: Mathematical, Physical and Engineering Sciences, Vol 460, pp2197-2221.*

Simonetti, F. a. (2005). On the nature of shear horizontal wave propagation in elastic plates coated with viscoelastic materials. *Proc Royal Soc Lond: Mathematical, Physical and Engineering Sciences, Vol 460, pp2197-2221.*

Sun, Z. Z. (2005). Flexural torsional guided wave mechanics and focusing in pipe. *ASME J Pressure Vessel Technology, Vol 127, pp471-478.*

The Guardian. (2011). *http://www.theguardian.com/business/2011/jan/10/bp-shuts-alaska-pipeline-after-leak*. Retrieved August 21, 2015

The Telegraph. (2013). *http://www.telegraph.co.uk/news/worldnews/asia/china/10469661/Death-toll-from-Chinese-pipeline-explosion-rises.html*. Retrieved August 22, 2015

Thompson., N. G. (2006). *Gas and liquid transmission pipelines.* Technical report, CC Technologies.

U45000990. (2008). *Non-destructive testing - Inspection of above-ground steel pipelines using guided waves.* Italian Organisation for Standardisation (UNI).

Uhlig, H. H. (1963). *Corrosion and corrosion control.* John Wiley & Sons.

Valle, C. N. (2001). Crack characterization using guided circumferential waves. *J Acoust Soc Am, Vol 110, pp1282-1290.*

Valle, C. Q. (1999). Guided circumferential waves in layered cylinders. *Int. J. Eng. Sci., Vol 37, pp1369-1387.*

Velichko, A., & Wilcox, P. (2009). Excitation and scattering of guided waves: relationshipos between soluition for free plates and pipes. *Journal of the Acoustical Society of America, 125*(6), 3623-3631.

Vicente, F., & Risso, E. (2008). *Argentine NGL case study applies economic procedure.* Neuquen: Oil & Gas Journal.

Vogt, T. L. (2003). The scattering of guided waves in partly embedded cylindrical structures. *J Acoust Soc Am, Vol 113, pp1258-1272.*

Vogt, T., & Evans, M. (2009). 4th European-American Workshop on reliability of NDE, We.4.A.3.

Wieslaw Ostachowicz, P. K. (2012). *Guided Waves in Structures for SHM.* UK: Wiley.

Wilcox, P. C. (1996). An example of the use of interdigital PVDF transducers to generate and receive a high order Lamb wave mode in a pipe. *Review of Progress in Quantitative NDE, Vol 16, DO Thompson and DE Chimenti (eds), Plenum Press, New York, pp919-926.*

Wilcox, P. E. (2003). Guided wave testing of rail. *Insight, Vol 45, pp413-420.*

Wilcox, P. L. (2005). Omnidirectional guided wave inspection of large metallic plate structures using an EMAT array. *IEEE Trans UFFC, Vol 52, pp653-665.*

Worden, C. R. (2007). An introduction to structural health monitoring. *Phil. Trans. R. Soc. A, vol. 365, p. 303.*

Yahya, M. F. (2010). *12" ACID SULPHURIC PIPELINE - 12-R17-031-II (01) - VISUAL AND UTTM INSPECTION REPORT.* TestEx (M) Sdn Bhd.

Zemanek, J. (1972). An experimental and theoretical investigation of elastic wave propagation in a cylinder. *Journal of the Acoustical Society of America, 51*(1), 265-283.

Zhao, X. a. (2003). Boundary Element modeling for defect characterization potential in a waveguide. *Int J Solids Struct, Vol 40, pp2645-2658.*

Zhao, X. a. (2004). Guided circumferential shear horizontal waves in an isotropic hollow cylinder. *J Acoust Soc Am, Vol 115, pp1912-1916.*

Zhu, W. (2002). An FEM simulation for guided elastic wave generation and reflection in hollow cylinders with corrosion defects. *Trans ASME J Pressure Vessel Technology, Vol 124, pp108-117.*

Zhuang, W. S. (1997). Axisymmetric guided wave scattering by cracks in welded steel pipes. *Trans ASME J Pressure Vessel Technology, Vol 119, pp401-406.*