

APPLICATION OF ULTRASONIC GUIDED WAVE FOR STRUCTURAL HEALTH  
MONITORING OF PIPELINE

MUKHLIS CHUA @ CHUA CHING KOK

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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 a point 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 pengesanan kecacatan yang biasa dihadapi iaitu lubang dan tampalan kakisan pada 12 inci untuk talian paip asid sulfurik. Pencapaian prestasi utama yang diperolehi 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**

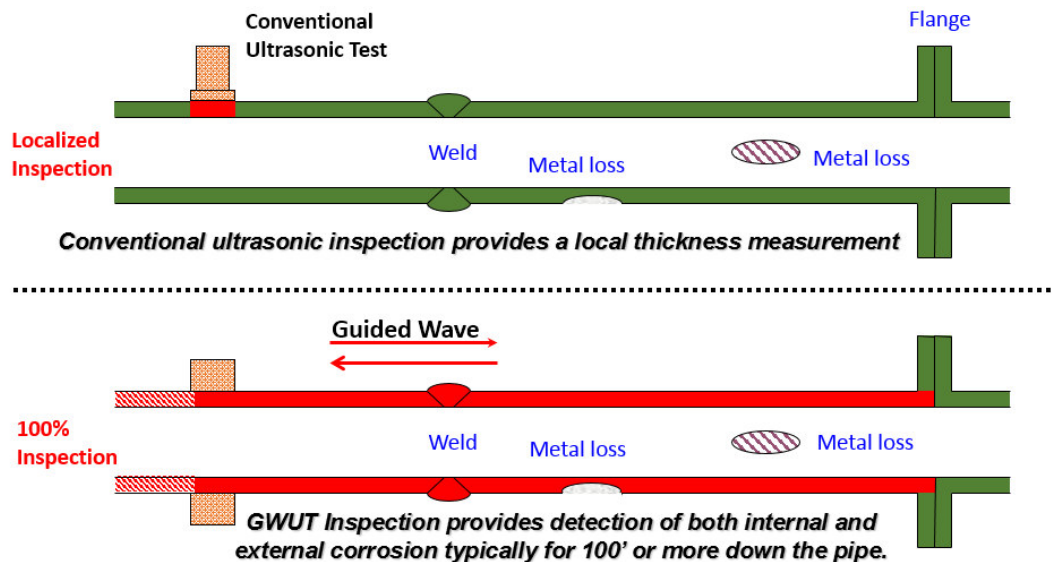
Guided Wave Ultrasonic Testing (GWUT) or Long Range Ultrasonic Testing (LRUT) is one of latest methods in the field of non-destructive evaluation. The method employs mechanical stress waves that propagate along an elongated structure while guided by its boundaries. This allows the waves to travel a long 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)

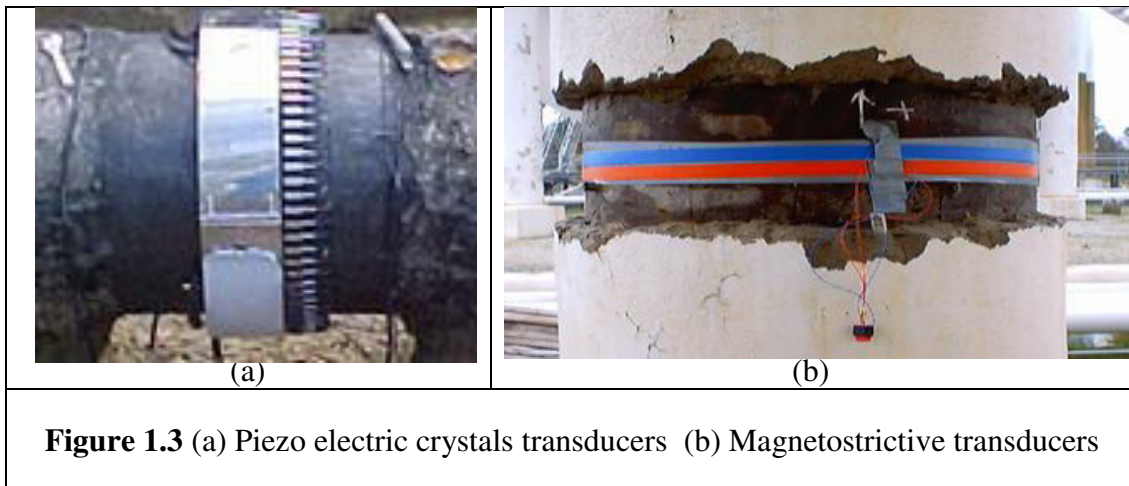
While conventional UT measures the wall thickness at a spot, advanced guided wave ultrasonic testing (GWUT) can identify locations of metal loss along a length of the pipe (Guided Ultrasonics, 2010).

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.



**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.



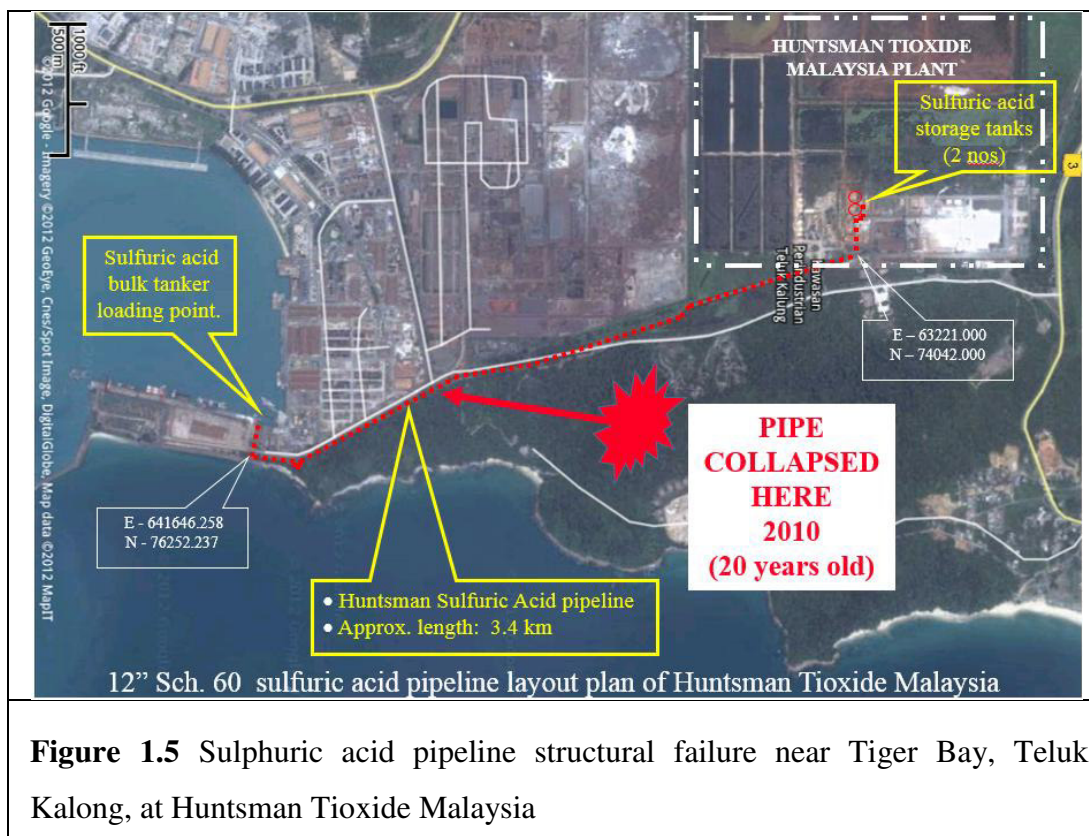
(a) Trans-Alaskan oil pipeline leak  
(The Guardian, 2011)



(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.

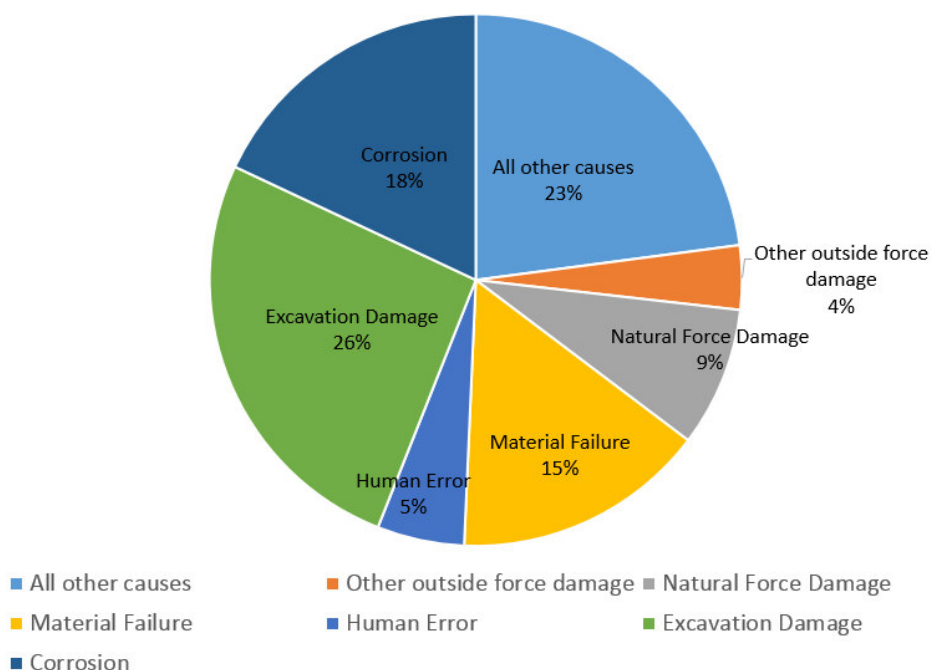
**Table 1.1** : Average annual consequences of significant corrosion incidents between 1988 and 2007 (Horrocks, et al., 2010).

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
<b>Total</b>	<b>1278</b>	<b>1659</b>	<b>52.1</b>	<b>1.45</b>	<b>5.1</b>	<b>26.9</b>

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).

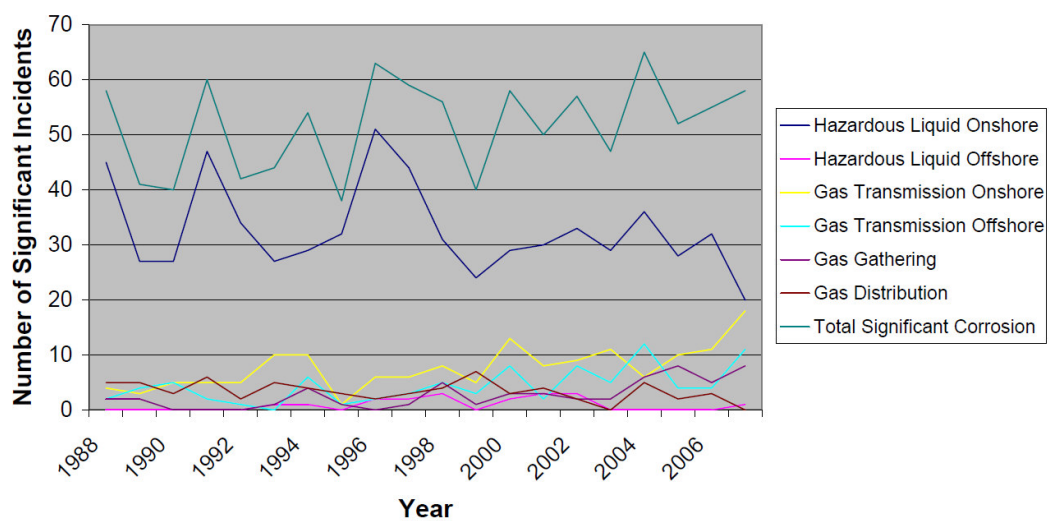
**All Pipeline Significant Incidents (1988 - August 2008)**



**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 offshore 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 a 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 Huntsman 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.

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