DETECTION OF MULTIPLE DEFECTS BASED ON STRUCTURAL HEALTH MONITORING OF PIPELINE USING GUIDED WAVES TECHNIQUE

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A thesis submitted in
fulfilment of the requirement for the award of the
Doctor of Philosophy

Faculty of Mechanical and Manufacturing Engineering
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APRIL 2018

I would like to dedicate this thesis to

MY PARENTS

and

MY FAMILY

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious, the Most Merciful. All praises be to Allah, the Supreme Creator, Nourisher and Sustainer of the universe. We beseech the Almighty to bestow His choicest blessings on our illustrious Master, Prophet Muhammad (peace be upon Him), on His pure family, His noble companions and all believers in every era.

I am extremely grateful to my supervisor; Assoc. Prof. Dr. Shahruddin Bin Mahzan for all the patience, guidance, advice, ideas, criticisms, encouragement and continuous discussions, my deepest gratitude goes to him.

I also, would love to extend my thanks to Prof. Dr. Ahmed N Abdalla at (UMP), who has encouraged me, until the end of my PhD journey. I am extremely grateful to all the laboratory staff in the NTD group inspection at the Faculty of Electrical, TATI University College, Kemaman, Terengganu, Malaysia. (Assoc. Prof. Dr. Ahmed N Abdalla, Dr. Damuji and Mr. Khruden Ali).

I am also indebted to all my family members, especially my wife, my sons, and my parents for their sacrifice, patience and understanding that have been very important in making the possible.

ABSTRACT

Monitoring and inspecting the health condition and state of the pipelines are significant processes for an early detection of any leaking or damages for avoiding disasters. Although most Non Destructive Test (NDT) techniques are able to detect and locate damage during the maintenance intervals, interrupted services could result in high cost and lots of time consumed. In addition, most NDTs are utilized to detect and locate single damage such as axial crack, circular crack, or vertical crack only. Unfortunately, these NDTs are unable to detect or localize multi-type of damages, simultaneously. In this research, the proposed method utilizes the Structural Health Monitoring (SHM) based on guided wave techniques for monitoring steel pipeline continuously in detecting and locating multi-damages. These multi damages include the circumference, hole and slopping cracks. A physical experimental works as well as numerical simulation using ANSYS were conducted to achieve the research objectives. The experimental work was performed to validate the numerical simulation. An artificial neural network was used to classify the damages into ten classes for each type of damage including circumference, hole and sloping cracks. The obtained results showed that the numerical simulation was in agreement with the experimental work with relative error of less than 1.5%. In addition, the neural network demonstrated a feasible method for classifying the damages into classes with the accuracy ranged from 75% to 82%. These results are important to provide substantial information for active condition monitoring activities.

ABSTRAK

Pemantauan dan pemeriksaan keadaan kesihatan dan tahap semasa saluran paip adalah satu proses penting untuk pengesanan awal kebocoran atau kerosakan bagi mengelakkan sebarang bencana. Walaupun kebanyakan teknik Ujian Tanpa Musnah (NDT) dapat mengesan dan mencari kerosakan semasa proses penyelenggaraan berkala, namun ianya melibatkan kos yang amat tinggi dan waktu yang panjang disebabkan oleh pemberhentian pengoperasian. Di samping itu, kebanyakan NDT hanya boleh digunakan untuk mengesan dan mencari kerosakan jenis tunggal seperti retak paksi, retak membulat atau retakan tegak sahaja. Oleh itu teknik NDT ini tidak dapat mengesan atau melokasikan pelbagai jenis kerosakan pada satu-satu masa. Dalam kajian ini, kaedah yang dicadangkan menggunakan teknik Pemantauan Kesihatan Struktur (SHM) berdasarkan teknik gelombang berpandu untuk memantau talian paip keluli secara berterusan untuk mengesan dan mencari pelbagai kerosakan. Kerosakan ini termasuk lubang lilitan, lubang dan keretakan. Kerja-kerja eksperimen fizikal serta simulasi berangka menggunakan ANSYS telah dijalankan untuk mencapai matlamat penyelidikan. Kerja-kerja eksperimen telah dijalankan untuk mengesahkan simulasi berangka. Rangkaian neural tiruan digunakan untuk mengklasifikasikan kerosakan kepada sepuluh kelas untuk setiap jenis kerosakan termasuk lilitan, lubang dan keretakan bercerun. Hasil yang diperolehi menunjukkan bahawa keputusan simulasi berangka telah mencapai hasil kerja eksperimen dengan ralat relatif kurang dari 1.5%. Di samping itu juga, rangkaian neural telah menunjukkan bahawa kaedah yang boleh dilaksanakan dalam mengklasifikasikan kerosakan ke dalam kelas dengan ketepatannya di antara 75% hingga 82%. Keputusan ini penting bagi membekalkan maklumat penting untuk aktiviti pemantauan keadaan aktif.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

Latin Script

A_0	fundamental asymmetric Lamb wave mode
c	speed of sound
c_g	group velocity
c^E	elastic stiffness constant matrix
c_l	longitudinal wave speed
c_p	phase velocity
c_t	transverse wave speed
d	half the thickness of the plate
D	matrix
D	electric displacement vector
E	Young's Modulus
E	electric field strength vector
e	piezoelectric stress constant matrix
e^t	transposed matrix
f	linear frequency
F(m,n)	flexural modes group
k	wavenumber
L(m,n)	longitudinal mode group
m	circumferential order of a mode
n	group order of a mode
S	strain vector
S_0	fundamental symmetric Lamb wave mode
T	stress vector
T(m,n)	torsional mode group
u	displacement vector

u_q	displacement in *q* direction
u_r	displacement in *r* direction
u_z	displacement in *z* direction
v	Poisson's Ratio of the material
y	perpendicular to the wave propagation direction

Greek Script

ϕ	dilatational scalar potential
λ	Lam'e constants
μ	Lam'e constants
ρ	density of the material
$\boldsymbol{\sigma}$	stress vector
ω	driving (angular) frequency
x	direction of wave propagation
ψ	vector potential
ε^S	clamping dielectric constant matrix
∇	Laplace operator
AE	Acoustic Emission
AFC	Active Fiber Composite
ANFIS	Artificial Neural Fuzzy System
ANN	Artificial Neural Network
BEM	Boundary Element Method
CWT	Continuous Wavelet Transform
DOE	Design of Experiment
DSP	Digital Signal Processing
I/M	Impedance Method
EMAT	Electromagnetic Acoustic Transducers
EMI	Electromechanical Impedance
FBG	Fiber Bragg Grating
FEA	ANSYS Finite Element Software
FEM	Finite Element Method
FFT	Fast Fourier Transform
FOS	Fiber Optic Sensors
GLW	Guided Lamb Wave

GPR	Ground Penetrating Radar
GW	Guided Waves
IIG	Integrated Impedance and Guided Wave
IR	Thermal/Infrared Testing
IWSHM	International Workshop on Structural Health Monitoring
LISA	Local Interaction Simulation Approach
LM	Laser Testing Methods
LT	Leak Testing
MFC	Macro-Fiber Composite
MFL	Magnetic Flux Leakage
MT	Microwave Testing
NDE	Nondestructive Evaluation
NDT	Non-Destructive Testing
NME	Normal Mode Expansion
NR	Neutron Radiographic Testing
NTSB	National Transportation Safety Board
PDF	Probability Density Function
PT	Liquid Penetrant Testing
PTM	Precursor Transformation Method
PVDF	Polyvinylidene Fluoride
PWAS	piezoelectric wafer active sensors
PZT	Piezoelectric Transducers
RAPID	Real-time Active Pipeline Integrated Detection
RSM	Response surface methodology
RT	Radiographic Testing
SH	Shear Horizontal
SHM	Structural Health Monitoring
STFT	Short Time Fourier Transforms
STMR	Single Transmitter Multi-Receiver
VA	Vibration Analysis
WT	Wavelet Transforms
WTC	Wavelet Transform Coefficient

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

The economy of countries in the world is heavily dependent on an extensive network of distribution and transmission pipelines to transport the countries' energy sources such as gas, oil and water. Petroleum in most developed countries is the largest source of energy transported using pipes. The network of pipelines has several advantages over other transportation methods such as trucks or trains due to effectiveness of cost, installation, and distribution inside cities. According to (Factbook, 2012), about 2,175,000 miles (3,500,000 km) of the pipeline have been installed in more than 120 countries in the world. However, many factors affect the pipelines network including corrosion, mechanical damages, and manufacturing defects. Environmental factors such as soil conditions where the pipelines are installed may also cause corrosion. Under extreme conditions, corrosion can impact the pipes' integrity as early as 5 years after installation (Kishawy & Gabbar, 2010). In addition, mechanical damages such as dents, gouges and removed metals can also impact the integrity of the pipelines due to the unsuitable handling of the pipes, unsuitable backfilling or running equipment too close to the pipe before it is backfilled (Macdonald *et al.*, 2007; Warman *et al.*, 2006). Moreover, several types of manufacturing defects could cause failure in pipelines' operations such as a defect in the longitudinal seam of the pipe which is the most common manufacturing defects. Figure 1.1 shows the statistics on what cause pipeline damages. Therefore, reliability and integrity of pipelines are significant conditions that grab researchers' attention for detecting and monitoring the degradation of the pipeline systems by regularly assessing their conditions.

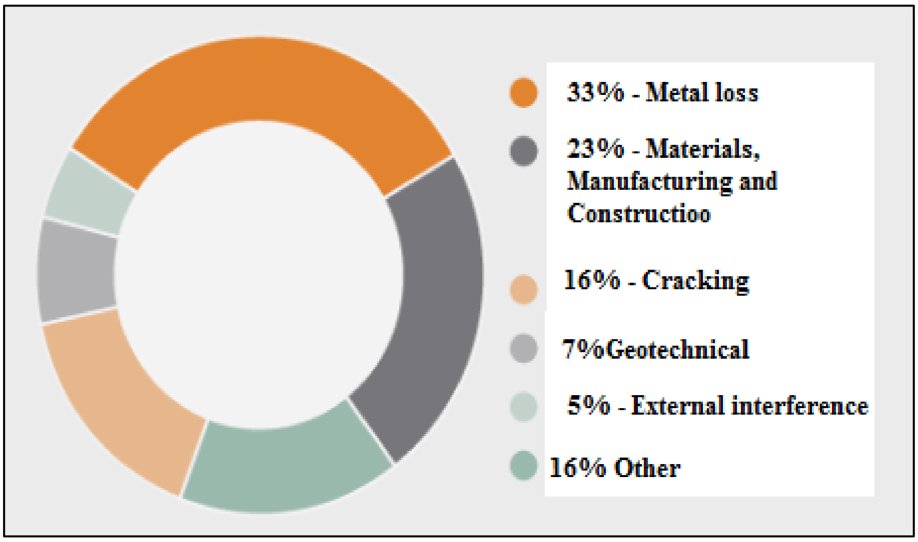

Figure 1.1: Actual damages that cause of pipelines incidents (Association, 2014)

1.2 Background

There are several and different methods (Carandente *et al.*, 2012; Eybpoosh *et al.*, 2016, 2017; Liu *et al.*, 2016; Løvstad & Cawley, 2011, 2012; Peter & Wang, 2013; Wang *et al.*, 2015; Wang *et al.*, 2010) that have been proposed and designed for inspecting, detecting, localizing and characterizing various types of damages. Industries typically implement a combination of several different destructive and non-destructive inspection techniques for inspecting and monitoring pipelines that are used for transporting oil and natural gas. These techniques are commonly used to ensure the integrity of pipelines. However, there are different factors that can be used to classify the existing techniques (Su & Ye, 2009). In this section, the applied current techniques are classified into destructive and non-destructive.

1.2.1 Destructive Testing techniques (DT)

Destructive testing (DT) is a technique in which the operation of the monitoring or inspecting needs to stop the functionality of the pipelines or temporarily taken out of operation. Most DT techniques are based on determining some mechanical properties, such as strength, toughness and hardness of the structure (Kang *et al.,* 2011; Puust *et al.*, 2010). Hydrostatic test is an example of the most common method used as DT. The test involves pressurizing the pipeline to a point greater than the maximum operating pressure. This is followed by observing the pressure for several hours to determine if there are any leaks. However, there are some drawbacks of using DT because of the potential risks that may arise during the test. These include leakage or rupture due to the high pressure. If this happens, the hazardous materials in the pipeline must be replaced with water to prevent environmental damage which causes service interruptions and water removal difficulties. Consequently, DT is considered as an unsuitable method for monitoring and inspecting the pipelines used for transporting natural gas and oil. In addition, DT is time consuming and need high cost.

1.2.2 Non-destructive techniques

Non-Destructive Testing and Evaluation (NDT/E) is the process of assessing the structural integrity of a material or component without causing any physical damage to the test object. Non-destructive techniques (NDT) have clear advantages over DT. The non-destructive techniques with pipelines typically involve a damage detection discipline commonly referred to as non-destructive evaluation (NDE). Generally, non-destructive testing (NDT) is used by the industry for assessing pipeline integrity and reliability (Shi & Miro, 2017; Varela *et al.*, 2015).It is an acceptable practice to detect dangerous defects before they cause catastrophic failure or interruption to production.

Recently, NDE conducted at regular scheduled intervals during the lifetime of engineered structures and assets, is clearly too unwieldy to achieve automatic damage identification when the structures and assets are in service (Qatu *et al.,* 2016). However, ND need to be performed at regular maintenance intervals which make ND does not provide on-line monitoring and detection of failures as they happen. To overcome the limitation of none on-line monitoring and detection of failures, researchers proposed a more reliable, economical monitoring system involves a damage detection process known as structural health monitoring (SHM) (Packo *et al.,* 2011; Yu *et al.,* 2008). In other words, SHM is defined as ‘the nondestructive and continuous monitoring characteristics using an array of sensors related to the fitness of an engineered component as it operates, so as to diagnose the onset of anomalous structural behavior (Kim & Kwon, 2015; Yang, 2009).

1.3 Problem statement

Although there are several SHM techniques being utilized for monitoring cracks in pipelines, there are some limitations whereby most existing detection and monitoring techniques are based on non-destructive techniques in which the detection requires a service interruption. In other words, this requires the pipeline system to be taken out for cracks inspection. Consequently, this interruption involves a high cost and lots of time. In addition, most existing techniques are implemented and used to detect specific and single type of crack such as axial crack (Liu *et al.*, 2017), circular crack (Wang *et al.*, 2015), or vertical crack only. Moreover, most existing techniques are able to detect cracks during maintenance intervals (as a basic requirement or regular maintenance intervals). Thus, these techniques could not provide continuous monitoring on the conditions of the pipeline for detecting cracks. Therefore, extra efforts are needed for an early detection of single or multiple damages in pipelines network using guided waves (GW) methods.

1.4 Research objectives

The goal of this research is to integrate a robust and reliable SHM technology with the GW-based Piezoelectric Transducers (PZT) sensor array system. The research objectives were identified as follows:

1. To develop an ANSYS model of guided waves, in order to acquire preliminary understanding of the guided waves in the pipeline and to obtain simulation data.
2. To assess and validate the Finite Element Analysis Simulation data with the experimental work.
3. To evaluate an SHM-based technology on GW technique for continuous monitoring steel pipeline and detect, locate, and characterize different types of damage(s).
4. To classify multiple damages (type, size, number, and location) using Artificial Neural Network (ANN).

1.5 Scope of the research

To achieve the objectives of the study, this work direction was limited to the following scope:

1. For oil supply, natural gas and industries pipelines network, a schedule 40 steel pipe was used and prepared for testing purpose in various research topics and damage detection in particular. It was difficult to obtain the pipe if it was purchased in a small quantity for an experiment as a non-commercial sample, were difficult to obtain and extremely expensive. In addition, the pipes' weight is quite heavy to suspend in the air with a plastic wire to prevent wave reflection. Therefore, a lighter and cheaper pipe was chosen as an alternative for the experiment. The selected material is a carbon steel pipeline (diameter 60mm, length 1000mm and 4mm thickness).
2. Three types of modes were generated when the waves were propagating along a cylindrical structure, which were: the longitudinal L(0,m), torsional T(0,m) and flexural F(n,m) wave modes. L (0,2) mode was propagated as if it was non-dispersive over the frequency range. Therefore, Guided waves propagation L (0,2) mode was used in hollow cylinders. In addition, this mode was not capable to detect axial damage, and therefore the artificial and simulated damages were circumference, holed, and sloped.
3. There are numerous elements to a pipeline system, including the main body of the individual pipe segments, flanged and welded joints, valves, fittings, and pumping stations. The waves suffered substantial dispersion and mode conversion that made it hard to analyze from the pipeline system. Therefore, the monitored area was the main body of the individual pipe segments only.
4. The simulations of perfect, cracks and holes pipes based on the ultrasonic guided-waves were conducted by using the ANSYS Finite Element Analysis Simulation software (FEA). The pipe structure with Guided waves simulated the pipes with the same parameters and boundary conditions.
5. The Artificial Neural Network (ANN) has been used for a wide range of applications such as diseases' diagnosis, mining gigantic data, speech recognition, image processing, pattern recognition, classification and prediction as well as many other applications. The ANN model was used to classify different damages through the use of Matlab software.

1.6 Thesis structure

This thesis is divided into five chapters and organized as follows:

Chapter One: Overviews the problem background. This is where the problem statement is introduced, and the objectives of this research are specified. In addition, the chapter states the scope of the research.

Chapter Two: In this chapter, an overview of SHM concepts and approaches and its applications are introduced. Moreover, it provides an overview about guided wave propagation in details. In addition, characteristics of piezoelectric effects and equations are presented. Finally, this chapter explains the artificial neural network.

Chapter Three: In this chapter, the research methodology is discussed and explained, and the main phases of experimental and numerical work were described. In addition, it provides the details of the experimental setup including overall pipeline inspection system. Finally, the Finite Element Analysis Simulation is also discussed, including finite element method and classification using artificial neural network.

Chapter Four: In this chapter, the results and finding of experimental work are explained together with the results and finding of ANSYS. Then the validation of the two results is presented and discussed. Finally, the classification of the damages based on confusion matrix is illustrated and discussed.

Chapter Five: This chapter summary of the results and conclusions are given. A brief discussion on the future recommendations is also presented. The conclusion, contributions of this study and the future works as well as the limitation of this study are presented.

CHAPTER 2

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