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NUMERICAL SIMULATION AND EXPERIMENTAL INVESTIGATION OF ULTRASONIC GUIDED WAVE PROPAGATION IN PIPES WITH DEFECTS

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By

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Thesis Submitted to the School of Graduates Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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July 2018

Chairman : Professor Ir. Faizal Mustapha, PhD
Faculty : Engineering

In-service pipelines are elongated structures which are widely employed to transport various types of liquid components and products in the gas, oil, and petrochemical industries. However, as pipelines age and encounter a number of changing environmental circumstances, defects such as corrosion and cracks can usually develop and affect the working condition of in-service pipelines. Defective pipelines can result in casualties, damage to the environment, litigation, high replacement costs, and property damage. In recent decades, ultrasonic guided waves (UGW) can detect corrosion and defects in pipes successfully, but the detection capabilities using the UGW technique are considerably affected by the complex profiles of the defects. The effects of notch depth, circumferential extent, frequency and pipe size on the reflection coefficient (RC) of the T(0,1) and L(0,2) modes were analysed numerically and experimentally. Good agreement was achieved between simulation and experimental results. The study shows that the RC of the T(0,1) mode obtained from the notches depends on the circumferential extent, notch depth and pipe size (diameter). A higher RC magnitude was obtained for 100% wall thickness notch, whereas the RC of the T(0,1) mode for 50% wall thickness notch was highly sensitive to frequency changes. Furthermore, the RC of the L(0,2) received from both notches was dependent on the notch depth and the pipe size. The effects of frequency on the RC was significant since a smaller RC magnitude was observed for the notch 50% through-wall depth than for the notch of 100% as the frequency changes. In addition, the propagation of the T(0,1) mode reflected from an axisymmetric circumferential notch (defect) with different depths and circumferential extents in steel pipes was parametrically studied using the finite element ABAQUS/Explicit software. The results show that the RC of the T(0,1) mode from the notch increases as the depth and circumferential length of the notch increase. Furthermore, the RC response is dependent on the changes in the cross-section area of the notch. The results reveal that the T(0,1) mode is sensitive to the circumferential axisymmetric defects of various depths and circumferential extents.

This study also attempted to approach a basis to use the GW technique for defect sizing in different pipe sizes by obtaining the RC from notches (defects) numerically. Finally, the results showed that it is possible to detect and size of various circumferential defects in different size of pipes when the T(0,1) or L(0,2) modes were incidents using this simulation models.

Abstrak tesis yang dikemukan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SIMULASI BERANGKA DAN PENYIASATAN EKSPERIMEN PENYEBARAN GELOMBANG ULTRASONIK BERPANDU DALAM KEROSAKAN PAIP

Oleh

AIDIN GHAVAMIAN

Julai 2018

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Simulasi Berangka dan Eksperimen Penyiasatan Penyebaran Gelombang Ultra bunyi di dalam Paip beserta kecacatan. Di dalam servis saluran paip, terdapat struktur panjang yang mana telah digunapakai untuk menyalurkan pelbagai jenis cecair serta produk seperti gas, minyak dan juga industri petro-kimia. Walaubagaimanapun, seiring dengan usia saluran paip yang ada serta terpaksa menghadapi perubahan iklim yang sentiasa berubah-ubah, kecacatan seperti penghakisan dan retakan akan berlaku dan mengganggu kerja-kerja servis saluran paip yang ada. Kecacatan pada saluran paip dapat mengakibatkan kematian atau kecederaan pada mangsa, kerosakan pada persekitran, litigasi, kos pembinaan semula yang tinggi serta kerosakan harta-benda. Sejak beberapa dekad yang lalu, Penyebaran Gelombang Ultra Bunyi (UGW) ini dapat mengenalpasti hakisan serta kecacatan pada saluran paip dengan berkesan, tetapi kebolehannya untuk mengenalpasti menggunakan teknik UGW ini dipengaruhi secara ketara oleh profil kecacatan yang kompleks. Kesan kepada kedalaman takuk, tahap ukur lilit, frekuensi dan saiz paip terhadap pekali refleksi (RC), mod T(0,1) dan L(0,2) mod di analisa secara berangka dan secara eksperimen. Persetujuan yang bagus di peroleh daripada keputusan simulasi serta eksperimen. Kajian mendapati RC pada mod T(0,1) diperoleh daripada takuk-takuk bergantung kepada kedalaman takuk dan ukur lilit malah bergantung juga kepada saiz paip (diameter). Magnitud RC yang tinggi diperoleh untuk 100% kedalaman dinding takuk, manakala RC untuk 50% kedalaman dinding takuk diperoleh adalah sangat sensitif kepada perubahan frekuensi. Lebih-lebih lagi, RC pada L(0,2) diterima daripada kedua-dua takuk adalah bergantung kepada kedalaman takuk serta saiz pipe. Kesan daripada frekuensi yang terdapat pada RC ada signifikan dimana nilai RC yang lebih kecil dilihat pada takuk 50% kedalaman terus-dinding lebih daripada takuk yang berada pada kedudukan 100% berikutan perubahan frekuensi yang berlaku. Tambahan pula, penyebaran mod T(0,1) direflek daripada ukur lilit axisimetri (kecacatan) dengan kedalaman serta panjang ukur lilit yang berbeza di dalam paip besi dikaji secara parametric menggunakan perisian elemen terhingga ABAQUS/*Explicit*. Hasil menunjukkan nilai RC pada mod T(0,1)

daripada takuk meningkat apabila kedalaman dan panjang ukur lilit juga semakin meningkat. Tambahan pula, respon RC bergantung kepada perubahan dalam luas keratan-rentas takuk tersebut. Hasil mendapati mod T(0,1) sensitive kepada kecacatan ukur lilit asimetrik dengan pelbagai kedalaman serta panjang ukur lilit. Kajian ini juga bertujuan untuk mendapatkan penggunaan asas teknik GW kepada kecacatan saiz yang berbeza diperoleh menerusi takuk RC (kecacatan) secara berangka. Akhir sekali, hasil kajian menunjukkan ianya berpotensi untuk mengenal-pasti kecacatan dan nilai saiz ukur lilit yang berbeza bagi saiz paip yang berbeza apabila mod T(0,1) atau L(0,2) adalah nilai kejadian yang menggunakan model simulasi.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

LRUT	Long Range Ultrasonic Testing
UGWs	Ultrasonic Guided Waves
FEM	Finite Element Method
FEM	Finite Element Modeling
FEA	Finite Element Analysis
GWs	Guided Waves
RC	Reflection Coefficient
SNR	Signal to Noise Ratio
FFT	Fast Fourier Transform
V_g	Group Velocity
V_p	Phased Velocity
DAC	Distance Amplitude Correlation

CHAPTER 1

INTRODUCTION

1.1 Research Background

As the backbone of gas and oil supply systems, pipeline networks can transport highly corrosive, high-pressure, and high-temperature content. Thus pipelines are very capable and reliable in meeting the demands of clients for gas and oil products at all times. There are several factors contributing to possible pipelines failures and to enhance their safety and integrity. The contributing factors include pipeline aging, corrosion, erosion, in-service damage, natural hazards, malfunctions, material defects, and interference of a third party which can result in the majority of unwanted consequences such as pipe defects, rupture, and puncture. Defective pipes may lead to fatalities, injuries, environmental damage, and loss of production. Some well-known failures such as the leaking oil pipeline of the corroded gas pipeline in Guadalajara City in Mexico (source: https://www.history.com/this-day-in-history/sewers-explode-in-guadalajara) and the trans-Alaska pipeline system (source: https:// www.propublica.org/article/oil-leak-is-latest-mishap-for-toubled-alaska-pipeline-system) are among failures that have caused human and financial losses. Thus, it is very important to improve the structural integrity and safety of a pipeline by performing regular In-Service Inspection (ISI) and, in this way, guarantee the protected running of the pipeline and avoid catastrophic failure (Galdos, Okuda, & Yagawa, 1990; Lee & Yang, 2010; Lin, Ito, Kawashima, & Nagamizo, 1999; Michael Lowe, 1998). Using conventional point-by-point Non-Destructive Testing (NDT) techniques, e.g. ultrasonic thickness gauging provides a slow process of inspection that raises the cost when comprehensive inspection coverage is necessary. Other NDT techniques for inspection including magnetic flux, eddy current, and radiography all require the pipe to be externally accessible. However, these techniques are often slow to cover the entire length of the pipe. Hence, it can be beneficial to look for a fast, accurate, and effective technique ideal for monitoring long distances of pipes just from one single transducer location to detect the regions where there might be corrosion, erosion or in-service damage. Whenever an initial fast monitoring test is carried out, conventional NDT methods can be used to focus on classifying the corrosion severity in the regions which have been detected earlier by the fast monitoring technique. In fact, the use of supplementary fast monitoring techniques helps accomplish the aims of detecting, locating, and sizing of defects such as corrosion and to minimise the overall costs of inspection. Regarding pipe inspection, one of the fast monitoring techniques is the pig technique that uses conventional ultrasonic bulk waves. In this case, the inside of the pipes can be monitored by sending an ultrasonic probe. This gathers the ultrasonic signals along the length of the pipe However, this method is really expensive when it comes to instrumentation and, additionally, it needs accessibility to launch and remove the pig. Hence, it is appropriate mainly for long-distances of large-diameter pipes (Cordell, 1994; Demma, 2003a; Williamson & Bohon, 1994). The GWs inspection technique is another online fast monitoring technique which can be used for detecting corrosion, erosion, and in-service damage in long-distance pipes. This technique has been widely applied in non-destructive evaluation because it has been recognised by many researchers or technicians as a fast, accurate, inexpensive, and effective technique for pipe inspection. It enables the inspectors to inspect pipes over tens of metres from only one single position of transducers distributed around the pipe circumference. In fact, the transducers excite cylindrically GWs and, subsequently, the waves stress the entire pipe wall and propagate along the pipe length. Then, they interact with all available features (such as corrosion patches, drains, branches, welds, etc.) which locally change the pipe geometry. Subsequently, the interaction will lead to wave scattering or partial reflection. Originally, the GWs technique was designed to inspect pipes in the range of 2 inch to 24 inch diameter; however, it can be used to inspect both larger and smaller sizes of pipe. The main application of the GWs technique is to inspect insulated pipes for corrosion under insulation (CUI), stainless steel pipes, high-temperature pipelines (<+125 °C), offshore risers (Na & Kundu, 2002; J. L. Rose, Cho, & Ditri, 1994), spirally welded pipes, painted pipework, road crossing sections, under supports, bridge piers, inaccessible pipework (i.e. buried pipes, sleeved, clamps, and cased pipes where rope access or scaffolding would be needed for tests using conventional NDT in the gas, oil, and petrochemical industries (DN Alleyne, Lowe, & Cawley, 1998; Demma, Cawley, Lowe, Roosenbrand, & Pavlakovic, 2004; Gan, 2010; Hirao & Ogi, 1999; Kundu, 2004; H Kwun, Kim, Choi, & Walker, 2004; Lebsack, 2007; Michael Lowe, 1998; MJS Lowe & Cawley, 2006a; M. J. Lowe, D. N. Alleyne, & P. Cawley, 1998; Marques & Demma, 2008; Placko & Kundu, 2013; Sens, 2007). In addition, GWs ultrasonic testing (GWUT) can be applied to test wind turbine towers and cables, railway lines, offshore platform jackets and plates (the walls and floors of steel plate structures such as pressure vessels and storage tanks) (Catton, 2009b; Demma et al., 2004; Na & Kundu, 2002; J. L. Rose et al., 1994; Paul Wilcox et al., 2003).

Structural defects can result from two factors: either they can arise because of (1) changes in material properties such as embedded structures in surrounding materials or they can be due to two different materials welded together or because of (2) geometrical defects for example: different corrosion defects, free ends, curved components connected to the principal structures, and welds joining a couple of components together (Demma, 2003a; Demma et al., 2004). Hence, understanding the effects of a geometrical defect in the structure (i.e. pipe) for practical applications is important to improve and develop an effective monitoring or inspection strategy (Demma, 2003a).

1.2 Problem Statement

In spite of the abundance of knowledge available regarding GWs propagation in pipes with defects, very little work has been carried out concerning the propagation of ultrasonic GWs in pipes of different sizes with rectangular circumferential notches of different size depths. On the other hand, the interaction of the GWs with defects in pipes is a complicated physical phenomenon which needs greater evaluation and explanation in both experimental and simulated cases before the general application of the GWs technique. In fact, to detect a problem in a pipe, the effect of essential parameters such as test frequency, defect sizes (e.g. defect depths) and the pipe diameter on the reflection coefficient (RC) of fundamental longitudinal or torsional GWs can be recognised and evaluated. (X. Wang, Peter, Mechefske, & Hua, 2010). Many investigations have been performed to determine the relationship between defect detection potential using GWs and reflections received from different types of defects in pipes affected by certain parameters, such as the axial and circumferential extents of defects, frequency changes and pipe size (diameter) (Bai et al., 2001; P Cawley, Lowe, Simonetti, Chevalier, & Roosenbrand, 2002; Zhou, Ichchou, & Mencik, 2009; W Zhu, Rose, Barshinger, & Agarwala, 1998). A recent study showed that small circumferential defects can be identified using the L(0,2) mode (Tan, Wang, Guo, & Ho, 2016). Moreover, previous studies found that the torsional T(0,1) mode around a pipe exhibited stronger reflection from axially aligned features or axial defects than the extensional (longitudinal) wave mode due to the circumferential motion of the former (MJS Lowe & Cawley, 2006b; Tan et al., 2016). However, in this research study; numerical and experimental analyses were performed to show the effects of notch depths, frequency and pipe size (diameter) on the RC of the T(0,1) mode from the circumferential notches (defects). Moreover, as yet this technique cannot provide a defect size. Both academics and industrialists recognise the potential for improvements to offer quantitative information concerning defect shapes or defect sizes, while providing the same fast inspection rates by using current commercial equipment. Therefore, the present research project focuses on the development of GWs technique to provide a deeper insight into the effects of various pipe sizes (4 inch, 6 inch and 8 inch) and different defect depths (here, the pipes have two notches (defects) at different depths (50 % and 100 % wall thickness) on the RC received from longitudinal and torsional GWs propagated at various test frequencies. As such, the work can provide greater detail for classifying the severity of defects by calculating the RC from the rectangular notches acting as defects. This development can be regarded as part of defect sizing prediction and estimation. If this can be accomplished and implemented commercially, then pipe inspection will become more cost-effective and, thus, more widely used. Since the final objective of all NDT research is to enhance the early detection of structural failure which causes pipe leaks, this research aims at improving the capability of this technique since a key application of this technique is in the gas, oil, and petrochemical industries for defect identification. In fact, the results of experimental investigation and numerical simulation of GWs propagation in different pipe sizes with defects of different sizes would be helpful in improving the capability of the GWs technique in relation to defect detection, location, and sizing, particularly, under inviolable or inaccessible conditions.

1.3 Objectives of the research

Based on the problem statement and limitations of the current commercial GWUT, the main objective of this research is to develop the capability of the GWs technique for detection, localisation, and even sizing of different defects in different sizes of pipe. This can be achieved through effective finite element simulation of the GWs propagation in different sizes of pipe with notch models. The GWs are excited by excitation nodes (transducers) encircling the circumference of the simulated pipes. In this regard, three sizes of steel pipes (4 inch, 6 inch and 8 inch) with two circumferential notches at different depths (50 % and 100 % wall-thickness) were simulated. The FE models were simulated using ABAQUS/Explicit software version 6.14-1.

In order to demonstrate the accuracy of the provided simulation, the GWs propagation along three steel pipes with two manufactured circumferential notches with the same size and position as those in the simulation, were analysed and investigated experimentally by employing Teletest transducer rings. Both longitudinal and torsional wave modes were excited to propagate along the pipe in both the simulation and the experiment. However, very limited prior works could be found through the application of the guided torsional T(0,1) wave to detect circumferential defects of varying depths in pipes. Moreover, past studies have indicated that the T(0,1) mode is not a good choice to detect circumferential defects. This is the motivation behind the use of the T(0,1) mode in this research to detect the varying size of circumferential notches in steel pipes. This approach can provide a basis to use the torsional T(0,1) for defect sizing in steel pipes by obtaining the RC from circumferential defects numerically and experimentally. Hence, there are three main questions as motivation to determine the greater capabilities of the GWs technique in corrosion monitoring of pipelines or piping systems. This technique can be usually used as a complementary technique along with conventional ultrasonic techniques during field inspections. One of the limitations of the technique is for sizing of defects. Hence this research study attempts to answer these three questions as follows: (1) is it possible to enhance the capability of the GWs technique using a novel FE simulation model for defect sizing in various sizes of pipes with circumferential notches (defects) of different depths and circumferential extent at a range of low frequencies from 30 kHz to 60 kHz; (2) is it possible to develop a novel finite element model to be used in the novel inspection system to help in the detection of circumferential defects by using the fundamental guided torsional T(0,1) mode; (3) what is the effect of pipe size, frequency and notch size (depth) on the RC received from defects.

The principal objectives of the current study project are:

- To numerically simulate and experimentally investigate the GWs propagation in three different steel pipe diameter sizes with two rectangular circumferential notches of different depths and location.
- To simulate the interaction of both longitudinal and torsional GWs with defects to determine the RC from both notches and to verify the simulation with the experimental data to validate the accuracy of the numerical simulation.
- To develop a new simulation model based on parametric studies for a circumferential defect in a pipe to detect and classify the severity of defects and also to predict the location and size of any types of defects based on the new introduced simulation model.

1.4 Scope of the study

The scope of this study concerns the development of the GWs technique by using a novel finite element model. FEM was used to examine 130 different simulation steel pipe models (three sizes of pipes) with two circumferential notches of different depths and locations in the pipes. Also, the same quantity of models was used for pipes without notches. Simulation models followed the same sizes of pipes with notches as used in the experiment. However, there was a lab limitation to use the same length and thickness of the pipes as in the experiment (see Table 4.2). Hence, the length and thickness of pipes of 4 inch, 6 inch and 8 inch were different in the experiments whereby the simulation models followed those sizes. The simulation and experimental tests were carried out at a range of frequencies between 30 kHz to 60 kHz.

Simulation and experimental verification provides a basis to conduct a parametric study for a novel inspection system. Ten different steel pipe models with varying depths and circumferential profiles were created in the parametric study. The results of this study yielded the RC of the two main guided wave modes (Longitudinal mode L(0,2) and torsional mode T(0,1)) from those notches. This novel inspection system not only performs detection and localisation of the defects in the different size of pipes but also it provides a basis for defect sizing. This developed monitoring system can be employed in a commercial GWs technique to enhance the efficiency of this method to detect, locate and size various types of defects in cylindrical structures such as pipes.

1.5 Organisation of this thesis

This thesis consists of five chapters, which are arranged to provide the research background, the literature review, the experimental tests, the simulation tests, parametric studies and the subsequent analysis and conclusions. The details of the chapters are summarised as follows:

Chapter 1 is the motivation, and the background is introduced in this study. This chapter also includes the scope and objectives of the research study.

Chapter 2 provides a summarised literature review of the GWs technique that explains the finite-element simulation fundamentals as well as the GWs theories regarding defect detection, localisation and defect sizing.

Chapter 3 describes the created finite-element models using ABAQUS/Explicit version 6-14.1 and the requirements of the simulation of GWs propagation in steel pipes, including explicit dynamic analysis, the Hanning window function, pure mode selection, element type, meshing, element size, notch modelling and defining a job for each model. This chapter, in addition, explains the experimental test process using the commercial UGWs technique and its application for the detection of manufactured notches in three pipes (4 in, 6 in and 8 in). Also, this chapter describes the axisymmetric and focusing technique for defect detection. Moreover, this chapter explains the parametric studies (including numerical models) that investigate the RC of the torsional T(0,1) mode from varying defect sizes of different depths and circumferential extents.

Chapter 5 explains the simulation results and experimental verification for GWs propagation and reflection in pipes with notches. This chapter explains parametric study results and describes the simulation of 130 different steel pipe models, including material properties, meshing, applying excitation force loads on excitation nodes (considered as transducers) and the required time steps and time increment in each model. Also, this chapter provides the simulation and experimental verification. Moreover, this chapter summarises the research study by explaining the conclusions obtained from experiment, simulation and parametric studies in this research work and finally provides recommendations for further studies.

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BIODATA OF STUDENT

Aidin Ghvamian was born in Tehran, Iran. He graduated as Bachelor of Materials Engineering in 2004 from the University of Azad Yazd. He pursued joint Mater's degree in Corrosion Engineering in 2009 from the University of Shiraz. Upon completing his degree, he worked in the field of NDT in Iran at TWI Persia Co. The author has the American Society of Non-Destructive Testing (ASNT) certificate of Ultrasonic Testing Level 1&2, Penetrant Testing Level 1&2, Magnetic Particle Testing Level 1& 2, Visual Testing Level 1&2, Radiographic Testing Level 1&2, Guided Waves Ultrasonic Testing Level 1, Phased Array Ultrasonic Testing Level 1&2 and Time of Flight Diffraction Level 1&2. He is presently enrolled as a full-time research in Aerospace Engineering Department at Universiti Putra Malaysia, Serdang 43400, Selangor. Malaysia. This research has been conducted by Aidin Ghavamian. He holds a membership of American Society of Non-Destructive Testing. He is a detail-oriented and performance-focused professional, with hands-on experience in all aspects of NDT and advanced NDT procedures and techniques; corrosion engineering; oil and gas pipeline integrity; material's engineering. Equipped with proven ability to analyze production material procedures; identify deficiencies, and develop operational solutions to drive productivity. Multifaceted and effective trainer with outstanding operational and managerial background; along with exceptional communication, analytical, technical, and problem-solving skills. Bilingual in Persian and English.

LIST OF PUBLICATIONS

Detection, Localisation and Assessment of Defects in Pipe Structures Using Guided Wave Techniques: A review, Aidin Ghavamian, Faizal Bin Mustapha, B.T Hang Tuah b.Baharudin, Noorfaizal Yidris submitted to Engineeing Structures

A pressure-based method for monitoring leaks in a pipe distribution system: A ReviewA Abdulshaheed, F Mustapha, A Ghavamian, Renewable and Sustainable Energy Reviews 69, 902-911

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