IMAGE RECONSTRUCTION TECHNIQUE VIA ULTRASONIC TOMOGRAPHY SYSTEM FOR METAL PIPE

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To my beloved wife and family

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ABSTRACT

Detection of concentration of the gas/liquid mixture inside the pipe with Ultrasonic Tomography (UT) has been investigated seriously with various researchers in the recent decade. To date, most of the researches of ut focus on Acrylic or PVC as pipe material. This research investigates the usage of metal pipe for ut application. The attenuation problem of metal pipe is due to high acoustic impedance mismatch between liquid and metal pipe. Based on the problems of metal pipe for application in the UT system, various alternatives are presented in this research. Modelling of the UT using COMSOL software is studied to visualize the real UT system. Various frequencies are tested to determine the optimum frequency of the UT system. The hardware of UT system is developed after selection of the suitable transceiver. The structures of the transmitter and receiver circuits are developed in order to improve the Signal to Noise Ratio (SNR) and functionality of circuits. The sampled signals are preceded to the computer via Data Acquisition (DAQ) system. Various algorithms are investigated to produce the best image reconstruction of the UT system. As the basic and convenient algorithm, Linear Back Projection (LBP) is used for reconstructing the primary image. Median Filter Back Projection (MFBP) and Disk Filter Back Projection (DFBP) are applied to improve the image quality of LBP algorithm. Additionally, the Circular Thresholding Segmentation (CTS) algorithm is applied to produce the segmented thresholding images. Based on the simulation results, 40 kHz is determined as the optimum frequency of UT system. The designed UT system for the metal pipe is experimentally tested and cross-sectional images are extracted from metal pipe. Additionally, this thesis presents the static and dynamic results of UT system from metal pipe. Based on the comparison between the performances of applied algorithms, the CTS algorithm has the best results due the minimum errors between original images and reconstructed images. The obtained results corroborate the

ABSTRAK

Pengesanan kepekatan campuran gas / cecair di dalam paip dengan tomografi ultrasonik (UT) telah dikaji secara serius oleh pelbagai penyelidik dalam dekad baru-baru ini. Setakat ini, kebanyakan kajian ut tertumpu kepada akrilik atau PVC sebagai bahan paip. Kajian ini mengkaji penggunaan paip logam untuk aplikasi UT. Masalah pengecilan paip logam terjadi disebabkan impedans akustik yang tinggi tidak berpadanan antara cecair dan paip logam. Berdasarkan kepada masalah paip logam untuk diaplikasikan dalam sistem UT, pelbagai alternatif dibentangkan di dalam kajian ini. Permodelan UT dengan menggunakan perisian COMSOL dikaji bagi menggambarkan sistem UT yang sebenar. Pelbagai frekuensi telah diuji untuk menentukan frekuensi yang optimum bagi sistem UT itu. Perkakasan sistem UT dibangunkan selepas pemilihan peralatan pemancar penerima yang sesuai. Struktur pemancar dan penerima litar dibangunkan bagi meningkatkan isyarat kepada nisbah bunyi (SNR) dan fungsi litar. Isyarat sampel didahului ke komputer melalui Sistem Perolehan Data (DAQ). Pelbagai algoritma dikaji untuk menghasilkan pembinaan semula imej terbaik bagi sistem UT itu. Sebagai algoritma asas dan mudah, Unjuran Belakang Linear (LBP) digunakan untuk membina semula imej utama. Penapis Median (MFBP) dan Penapis Cakera (DFBP) digunakan untuk meningkatkan perbezaan kesan kabur LBP. Selain itu, algoritma Segmentasi Ambang Bulat (CTS) digunakan untuk menghasilkan imej ambang bersegmen. Berdasarkan kepada keputusan simulasi, 40 kHz ditentukan sebagai frekuensi optimum bagi sistem UT. Sistem UT yang dibangunkan untuk paip logam diuji dan imej seksyen silang dikeluarkan dari paip logam. Selain itu, tesis ini mempersembahkan hasil statik dan dinamik bagi sistem UT daripada paip logam. Berdasarkan perbandingan antara prestasi algoritma yang diguna, algoritma CTS mempunyai keputusan yang terbaik kerana mempunyai kesilapan yang minimum antara imej asal dan imej yang dibina semula. Keputusan yang diperolehi menyokong kebolehgunaan sistem UT yang

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION

AC	-	Alternating Current
ADC	-	Analogue-to-Digital Converter
CAT	-	Computerised Axial Tomography
CPU	-	Central Processing Unit
CS	-	Control Signal
CT	-	Computerised Tomography
CTS	-	Circular Thresholding Segmentation
DA	-	Dielectric Absorption
DAQ	-	Data Acquisition System
DC	-	Direct Current
DCU	-	Digital Controller Unit
DFBP	-	Disk Filtering Back Projection
ECT	-	Electrical Capacitance Tomography
EIT	-	Electrical Impedance Tomography
EMT	-	Electromagnetic Tomography
ERT	-	Electrical Resistance Tomography
GUI	-	Graphical User Interface
IC	-	Integrated Circuit
ICSP™	-	In-Circuit Serial Programming™
IPT	-	Industrial Process Tomography
LBP	-	Linear Back Projection
MATLAB	-	Matrix Laboratory
MCU	-	Microcontroller Unit
MFBP	-	Median Filtering Back Projection
MIPS	-	Million Instruction Per Second
MRI	-	Magnetic Resonance Imaging

NMR	-	Nuclear Magnetic Resonance
Op	-	Amp - Operational Amplifier
PC	-	Personal Computer
PCB	-	Printed Circuit Board
PCI	-	Peripheral Component Interconnect
PET	-	Positron Emission Tomography
PT	-	Process Tomography
RISC	-	Reduced Instruction Set Computer
RS232	-	Recommended Standard 232
SHA	-	Sample and Hold Amplifier
SnH	-	Sample-and-Hold
TI	-	Texas Instruments
USB	-	Universal Serial Bus
UT	-	Ultrasonic Tomography
UTT	-	Ultrasonic Transmission Tomography

LIST OF SYMBOLS

–	-	Average Mean of Matrix A
-	-	Average Mean of Matrix B
A_G	-	Percentage of Gas Area
$Agas$	-	Measured Gas Area
A_L	-	Percentage of Liquid Area
$Aliquid$	-	Measured Liquid Area
$B\ (x,y)$	-	EPR Marking Matrix
c	-	Velocity of Sound
C	-	Capacitor
C_{max}	-	Maximum Concentration
C_{Th}	-	Concentration Threshold
d	-	Diameter
dB	-	Decibel
E_a	-	Estimated Gas Area
F_c	-	Center Frequency
fps	-	Frames per second
Gas_Down_{xy}	-	Simulated Gas Bubble (Downstream)
Gas_Up_{xy}	-	Simulated Gas Bubble (Upstream)
Gas_{xy}	-	Simulated Gas Bubble
kHz	-	Kilohertz
L	-	Distance
M_a	-	Measured Gas Area

ME	-	Measurement Error
MHz	-	Megahertz
M_P	-	Maximum Total Pixels
$M_{Tx,Rx}(x, y)$	-	Normalized Sensitivity Matrices
N_{delay}	-	Number of Delayed Frames
nF	-	Nanofarad
Pgas	-	Gas Component Percentage
Pliquid	-	Liquid Component Percentage
P_r	-	Reflection Coefficient
P_t	-	Transmissions Coefficient
R	-	Resistor
Rx	-	Receiver
SimMap	-	Simulated Phantom Matrix
Sim_x	-	Simulation Profile
SnH	-	Sample-and-Hold
S_{TxRx}	-	Sensor Loss Voltage
t_s	-	Observation Time
Tx	-	Transmitter
V	-	Flow Velocity
V-	-	Inverting Input
$V(x,y)$	-	Concentration Profile
V+	-	Non-inverting Input
$V_{EPR}(x,y)$	-	Concentration Profile using LBP
$V_{LBP}(x,y)$	-	Concentration Profile using LBP
V_{p-p}	-	Voltage Peak-to-Peak
V_{ref}	-	Voltage Reference
$V_{ref\ TxRx}$	-	Reference Sensor Voltage

V_{Supply}	-	Voltage Supply
V_{TxRx}	-	Measured Sensor Voltage
Z	-	Acoustic Impedance
ρ	-	Density
τ	-	Transit Time
f	-	Frequency
α	-	Attenuation Coefficient
λ	-	Ultrasound Wavelength
$^\circ$	-	Degree
μF	-	Microfarad
2D	-	Two Dimensional
3D	-	Three Dimensional

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

The root of tomography word belongs to the Greek language. It consists of “Tomo*v*” and “Graph” which mean “to slice” and “picture”. The concept of “to slice” relates to the cross section of any object. In other word, the definition of tomography word can be stated as a process for obtaining the cross sectional images from an object [1].

For the first time in 1950’s, the development of process tomography started and has a wide application in medicine especially for body scanning in that time. However, it still is used as the efficient instrument in medicine for scanning application in various proposes [1]. Evaluation of process tomography carried out during the mid-1980. Various imaging equipments for tomography processes was presented in the 1970’s, but it involved using ionization in x-rays, etc. The present progress on process tomography systems are achieved due to the accomplished researches in mid- 1980’s. Generally, process tomography is a technique used to determine the internal behaviours of flowing materials in a pipeline [2]. It used to demonstrate the internal composition of pipes or mixing vessels in the images form. There are many different types of tomographic methods which are used to obtain different kinds of readings. For example, the significant part of the tomography system which leads to the creation the different types of tomography system would be the applied sensors. The applied sensors mount around a cylindrical vessel or object for obtaining different measurement readings through the device under test [2].

According to the potentiality of process tomography for improvement of efficiency and safety in process industries with changing the material of the container of fluid, it is still investigated by the researchers which results to the design of new circuit structure for transmitting and receiving signals or new reconstruction algorithms to improve the quality of images. Both qualitative and quantitative data needed in modelling a multi-phase flow system can be achieved by use of this system. In tomography, multiple projections with the use of various sensors are used to obtain sets of data from various views across the process vessel. These data are used to provide tomographic cross sectional images representing the contents of the pipeline or vessel. The plane image of objects provides an opportunity to reveal the complexities of structure without invading the object [3].

The efficiency of tomography systems increases with an increment of the quantity and quality of data due to many earlier measurement techniques [4]. In this research ultrasonic sensor array is selected to mount on the periphery of the pipe for collecting the data from inside the pipe. According to designed and manufactured tomography systems to date, most of the systems have been implemented on acrylic pipes or polyvinyl chloride (PVC) pipes but metal pipes are not used for the container of multi fluid flow. It is because of the various difficulties in ultrasonic wave propagation and the point is that longitudinal mode of wave propagation is our desired mode and the other modes of propagation make problems in sensing process. Additionally, due to the large difference between acoustic impedance of metal layer and liquid layer, a few percentage of ultrasonic energy can penetrate on the inside of the pipe and consequently the received energy by the receiver sensors is very low percentage of transmitted energy. In this research ultrasonic sensor array will be mounted on the surface of metal pipe.

The first non-invasive of ultrasonic tomography (UT) fabrication technique was introduced by Gai [5]. Improvement on the mentioned research work is not longer investigated. Development on UT has focused more to liquid/gas two-phase flow [6 and 7] where the Perspex pipe has been used as conveyor. However, the latter system has been implemented in the invasive mode which is not supported mostly by the industries. Three transmitters have been implemented in non-invasive system and for exciting the mentioned transmitters; a signal with 200V amplitude was applied to the transmitters [7].

1.2 Problem Statement

Various investigations on process tomography with different kinds of sensors are carried out. For instance, adopting ultrasonic sensors in process tomography was introduced by Gai [5] when they presented their research on the non-invasive UT fabrication technique. The history of UT pursuit with the carried out developments on measurement of liquid/gas flow [6 and 7]. The latter system which implements invasive technique of sensing is mostly not favored by the industries. Additionally, the proposed technique by Xu *et al.* [7] utilized high excitation voltage (around 200V) for the excitation of ultrasonic transmitters. This is however troublesome and the electrocution danger or technical breakdown would be dangerous if any fault accidentally appeared to be in the system. Nevertheless, the high excitation voltage has put a restriction on the system and also the application [8].

The latest development on UT by Rahiman [8] however have solved the earlier problems described. The implemented system have successfully developed an UT system using low operating voltage transducers (20V) which has been proved to be sufficient for liquid/gas flow imaging as long as the acoustic energy could pass through the process vessel [8]. More importantly, the developed system has successfully implement 16-pairs of ultrasonic transducers for non-invasive ultrasonic measurement system. The non-invasive transducer fabrication techniques were realised by using silicon grease as the acoustic coupling to ensure ultrasonic waves to be able to penetrate the process vessel.

In the pursuit of continuing the previous research done specifically in UT, this research is motivated by the opportunity to increase the capability of an UT system and widen the range of application where it can be utilized. Compared to conventional measurement techniques, process tomography measurement technique is essential to give an insight into phase interactions and help in providing better understanding of the operation process, which such information is useful for system design and control.

In light of this issue, the main limitations of the previous development on UT systems are as:

i. Application of metal pipe in UT system. To date majority of investigations in UT system are restricted to the pipes with material of Acrylic or PVC [9-25].

ii. Improving the spatial resolution of generated images with UT system. It is still a challenge between researchers to develop a new image reconstruction algorithm in order to increase the spatial resolution of images [13, 23, 26-40].

These limitations are considered in this study. Awareness on some of the deficiency or opportunity for enhancing the advantage of such system for industrial environment where metal pipes apply for the transfer of the materials, new design and more others can be implemented and exploited which is discussed in upcoming chapters.

1.3 Research Objectives

The main objective of this research is generating cross-sectional images from metal pipe with UT system. Based on the main objective, other objectives of this research are listed as follow:

1. To simulate and model the tomography system to find the optimum sensor for metal pipe.

2. To implement ultrasonic transducers non-invasively on the periphery of the metal pipe and designing the suitable electronic circuit as the transmitter and receiver circuit for supporting the 16 applied ultrasonic sensors.
3. To implement suitable algorithm for the image reconstruction.

1.4 Research Methodology

The approach that will be used in this research is a non-invasive technique where 16 ultrasonic transceivers will be mounted on the surface of a metal pipe. By the considering the method of non-invasive technique and developing the systems for an industrial applications [31] cause to arise the ideas which listed as follows:

i. Acoustic impedance plays a main role in transmitting the ultrasonic energy from one layer to another layer. Due to the impedance mismatch between air and the surface of the pipe so using the ultrasonic method in air is very inefficient and large amount of ultrasonic energy is attenuated [31]. When ultrasonic transducers mount on the surface of the pipe, air gap may be trapped between the surface of the transducer and surface of the pipe that it cause to large amount of ultrasonic energy is reflected and cannot transmit on the wall of the pipe. To solve of the mentioned problem, an acoustic coupling should be equipped between the sensors and the outer pipe surface so that the ultrasonic wave could transmit on the pipe.

ii. The high difference of acoustic impedance between metal pipe and liquid inside the pipe results to the high value reflection of ultrasonic wave at the interface of liquid and metal pipe. Due to the high reflection property of metal pipe for the ultrasonic wave, low amount of ultrasonic energy can penetrate inside the metal pipe. In order to solve this problem, high amplitude of ultrasonic wave should be applied on the metal pipe.

iii. Ultrasonic transducers must be suitable to the application design where the transducers projection should be in a wide angle and they can support high amplitude voltages. Wide beam angle is because of the straight-line propagation of ultrasonic waves has been used in this system. High amplitude voltage supporting of sensors is because of the high attenuation of ultrasonic wave along the transmission path from transmitter to receiver.

iv. Since the metal pipe has been applied as the conveyor of tomography system, the manner of ultrasonic wave propagation is notable. In this tomography system straight line propagation of wave (longitudinal mode) is our favorite mode. When ultrasonic wave transmitted on the wall of metal pipe, other modes of propagation such as shear mode, surface mode and lamb wave are also resulted. Lamb wave propagation on the wall of the pipe is parallel with shear wave and it can make a problem in sensing procedure. Lamb wave is proportional with the ultrasonic frequency so it is important an optimum frequency is determined for the exciting frequency of ultrasonic transducers.

v. Two types of signal can be used as the exciting signal of transducer: Continues and pulse signals. Since continues signals make the standing waves so pulse signal is generated. The pulse signal should ideally be software controlled so that the timing of the pulses can be easily varied and the synchronization is ensured. Additionally, the pulse signal should be long enough for the transient response and it is short enough to avoid multiple reflection and overlapping receiver signals. The mentioned terms achieve by the use of microcontroller.

vi. At the receiving part of the system, very low percentage of transmitting energy can be achieved at the other side of the pipe and due to the lamb wave problem that it is assumed as a noise of system cause to disappear the low voltage signal which is transmitted in straight line. A low-noise signal conditioning circuit is required to increase signal to noise ratio and amplify the ultrasound receiving signal.

1.5 Research Scope and Limitations

The research scopes are divided into six main parts. They are the designing of transducer fixture, suitable ultrasonic transducer and coupling material, suitable frequency for the resonance frequency of transducers, the electronic transmitter circuit, the electronic measurement circuit, the digital controller and the data acquisition system. The details are explained as following:

i. Designing of transducer fixture

The design of fixture of holding the ultrasonic transducers includes the mechanical structure of the fixture, the geometry of the transducers, the angle of transducer’s projection beam, and the cost effective to the design.

ii. Suitable ultrasonic transducer and coupling material

The design includes the selection of suitable ultrasonic transducer that it can support the high voltage amplitude and it has wide angle beam projection profile. The couplant is also should be suitable with the experimental environment and the handling feasibility.

iii. Suitable frequency for the resonance frequency of transducers

The selection of a proper frequency as an exciting frequency includes the consideration of the straight line propagation of wave and decrease the length propagation of the lamb wave. Lamb wave has the noise role in this kind of measuring and it makes a problem due to the time of flight Lamb wave is more quick than straight line wave and due to the low amplitude of the received straight line signal, Lamb wave cause to disappear the affection of straight line signal and it can be control by the exciting frequency.

iv. The electronic transmitter circuit

The design includes the ultrasound signal generator, designing a switching high power amplifier, isolator for isolating the high power part from low power, transformer for impedance matching of the system. Finally they are implemented in printed circuit board (PCB) for reduce the noise affection.

v. The electronic measurement circuit

The design of the measuring circuit in receiving part of the system include the selection of effective low noise amplifier integrated circuit (IC) and using an appropriate amplifying technique, the signal processing circuit using the sample and hold technique to convert the analog signal to digital. The printed circuit board (PCB) layout and implementing the components properly is needed to reduce the noise within the circuits.

vi. The digital controller and the data acquisition system

The design includes the microcontroller programming, the ultrasound projection sequence, delay estimation between pulses for preventing the overlapping problem, the determination of observation time (*ts*) for estimation of the time of flight of each sensor, the sample and hold triggering signal to convert the analog signal to digital and finally the synchronization of data acquisition by implying the controlling pulse signal to start and stop the operation.

The limitations of UT system due to the physical property of ultrasonic wave are as follow:

i. The main affection of ultrasound wave frequency is the sizes of the particles or bubbles being comparable with the wavelength of the ultrasound, therefore in practice unpredictable scattering, reflection and mode changing can be occurred in real work. The size of gas bubbles in the sensing zone should be greater than at least half wavelength of the ultrasonic wave in order to block the ultrasonic wave from reaching to the receiver sensors during the measurement process [41 and 42]. Due to the application of the 40 kHz ultrasonic sensors in this system, the minimum detectable size of bubbles is 19 mm.

ii. Since ultrasound travels too slowly, so it is not proper to give high-resolution images of fast moving flows in large pipes. The speed of ultrasound in water is about 1500 m/s or 1.5 mm/μs [43]. Based on the configuration of hardware of UT system, the total time for generating the cross-sectional image due to the one complete scan of metal pipe is equal to 1.4 seconds.

iii. The presented UT system in this research can only be used in the sparse bubbly flows. When so many gas bubbles exists inside the pipe in the sensing area, and the distribution area of the gas bubbles in the cross section of the pipe is larger than the axial aperture of the used pipe; then ultrasonic wave cannot pass through and reach the receiver sensor along a straight line [3]. Only 20% of total holdups such as gas bubbles or solid particles would be reliable limit for the monitoring of the flow with UT systems.

1.6 Thesis Organization

Chapter 1 as have been gone through describes the definition of tomography and its brief history, along with an overview of this research. This chapter also states the research's background problems, the problem statements, and the importance of the study, the research methodology, the research's principal aims and objectives which is believed to benefit wide range of differential applications. Additionally, the limitations of current UT system are presented.

Chapter 2 presents an introduction to the process tomography, including the lists of the most common tomography techniques summarizing their working principles, advantages and disadvantages. Fundamentals on the use of ultrasonic sensing for imaging instrument are compiled specifically for understanding the key aspects.

Chapter 3 is about the basic and fundamental governed theories in UT systems. Due to the complex behaviour of ultrasonic wave when propagate within the metal pipe, theory of ultrasonic wave is utilized for estimating the ultrasonic wave behaviour in metal pipes. In this chapter, the essential theory of the simulation with COMSOL software will be presented. In this research COMSOL software is used in order to determine the suitable sensor for the UT system with metal pipe conveyor. The basic and conventional image reconstruction algorithms also will be presented at the end of this chapter.

Chapter 4 is divided to two main parts: Hardware development and Software development of UT system. It starts with the production of the experimental setup which includes the metal pipe and base holder design and also the rapid prototyping mechanical works for producing the sensors fixture. The main step in this research is finding the proper sensor for the case of metal pipe. For this purpose, various simulations with COMSOL software are carried out to find the optimum frequency as the resonance frequency of the applied sensor. Detailed explanation on each parts and its importance to the whole system is presented including various other sub-systems such as the ultrasonic sensor, electronic circuitry, embedded system, PCB design and finally the data acquisition module. Programming structures are charted to illustrate all software-wise mechanisms. Additionally, this chapter is focused on explaining the software development. Virtual projection of the ultrasound propagation is mapped and used by the proposed algorithms for image reconstruction where composition determination and error measurement are calculated. The structure for constructing the application software providing the graphical user interface are given in details in associated flow chart. Additionally, several types of functions that are designed for operating the measurement process are also discussed.

Chapter 5 exposed all the achieved results from simulation with COMSOL regards to the finding the optimum frequency and identification of the sampling method form received signals, results from forward modeling of UT system and resultant cross-sectional images form experimental static UT system by inserting hollow PVC pipe inside the metal pipe. The dynamic results of UT system with metal pipe for bubbly flow are illustrated in this chapter. The results are analysed on its imaging capabilities specifically in a metal pipe configuration, the recorded measurement of liquid and gas component distributions inside the metal pipe and error measurement from the actual value.

Chapter 6 concludes the research findings throughout the dissertation including discussing significant contributions towards process tomography community particularly on the subject of ultrasonic tomography. Recommendations for future works are also addressed to assist other researchers in pursuing the works for further development and improvement.

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