2 MHz ELECTRICAL RESISTANCE TOMOGRAPHY FOR STATIC LIQUID-SOLID PROFILE MEASUREMENT

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In the name of Allah, the most Gracious and the most Merciful.

To my beloved and supportive parents,

husband,brothers, sisters

and

my lovely children

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ABSTRACT

Tomography is a technique used to reconstruct cross-sectional image of a pipeline for flow monitoring applications. There are several types of tomography system such as X-ray tomography, ultrasonic tomography, and electrical resistance tomography (ERT). ERT has many advantages compared to other types of tomography such as low cost, robust and no radiation. Thus, it becomes particularly suitable for industrial applications. However, it has been observed that the conventional practice of ERT through invasive sensing technique has exposed the ERT metal sensor to corrosion and limited its application because of inaccurate measurement of the data. Consequently, non-invasive ERT has also been introduced in low frequency (in kHz) applied to the ERT system. The low frequency ERT makes use of the phase-sensitive demodulation (PSD) approach and is a complicated technique to implement. Hence, the goal of this research is to design and develop a non-invasive ERT system with a high frequency (2 MHz) source. A total impedance of coupling capacitances (between metal electrode and conductive medium) series with resistance (conductive medium) for each pair of electrodes was assumed in the research. Based on the mathematical equation of the total impedance, the real part is the resistance (conductive medium) must be larger than the imaginary part (capacitances), so that it can easily detect the concentration profile of the conductive medium. Therefore, the minimum frequency needed to ensure that the real part is bigger than the imaginary one is 2 MHz. Simultaneously, the independent and flexible sixteen ERT electrodes designed for the system make it easier to replace and troubleshoot any problems with the sensor. In addition, the experiment was carried out on a two-phase static liquid–solid regime for a linear back-projection algorithm using online configuration, with MATLAB as a software platform. It was also able to detect and visualize the non-homogenous system of the two-phase regime. Later, the reconstructed image was improved using a global threshold technique through offline configuration. The experiment results indicate that it could detect obstacles in a vertical pipe with minimum 12 mm in diameter and 4.5 cm in height.

ABSTRAK

Tomografi merupakan satu teknik yang digunakan untuk menggambarkan keratan rentas bagi saluran paip dalam aplikasi-aplikasi pemantauan aliran. Terdapat beberapa jenis sistem tomografi seperti tomografi X-ray, tomografi ultrasonik, dan tomografi rintangan elektrik (ERT). ERT mempunyai banyak kelebihan jika dibandingkan dengan jenis-jenis tomografi yang lain seperti kos yang rendah, kukuh dan tiada radiasi. Maka, ia sangat sesuai untuk aplikasi industri. Tetapi, konvensional ERT melalui teknik penderia invasif menyebabkan penderia logam ERT terdedah kepada kesan kakisan dan ia menghadkan penggunaannya kerana pengukuran data yang tidak tepat. Maka, teknik penderia bukan invasif juga telah diperkenalkan dengan menggunakan frekuensi yang rendah (dalam kHz). Frekuensi rendah memerlukan kaedah penyahmodulatan peralihan fasa (PSD) dan ianya merupakan teknik yang rumit untuk dilaksanakan. Oleh itu, matlamat kajian ini adalah untuk mereka bentuk dan membangunkan sistem ERT tidak invasif dengan menggunakan sumber frekuensi yang tinggi (2 MHz). Anggapan jumlah galangan bagi setiap pasangan elektrod dengan mengambil kira gandingan kemuatan (antara elektrod logam dan bahan konduktif) sesiri dengan rintangan (bahan konduktif) digunakan dalam kajian ini. Berdasarkan persamaan matematik bagi jumlah galangan tersebut, bahagian nyata mesti lebih besar daripada bahagian khayalan supaya lebih mudah untuk mengesan profil kepekatan bahan konduktif. Maka, frekuensi minimum yang diperlukan untuk membolehkan bahagian nyata lebih besar daripada bahagian khayalan ialah 2 MHz. Pada masa yang sama, enam belas elektrod ERT yang telah direka secara individu dan fleksibel membolehkan penderia lebih mudah diperiksa dan ditukar. Sebagai tambahan, eksperimen telah dijalankan terhadap dua fasa cecair-pepejal rejim yang statik untuk algoritma unjuran kembali linear menggunakan konfigurasi terus, dengan MATLAB sebagai platform perisian. Ia juga telah dapat mengesan dan memberi gambaran bagi sistem dua fasa yang bukan homogen. Kemudiannya, kaedah ambang global melalui konfigurasi tidak terus untuk penambahbaikan gambaran tersebut telah digunakan. Keputusan eksperimen juga telah menunjukkan sistem ini boleh mengesan objek dalam paip menegak dengan ukuran diameter minimum ialah 12 mm dan tinggi sekurang-kurangnya 4.5 cm.

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LIST OF ABBREVIATIONS

ERT	—	Electrical resistance tomography
ECT	—	Electrical capacitance tomography
kHz	—	Kilo hertz
PSD	—	Phase-sensitive demodulation
MHz	—	Mega hertz
PT	—	Process tomography
DAS	—	Data acquisition system
EIT	—	Electrical impedance tomography
UT	—	Ultrasonic tomography
LBP	—	Linear back-projection
FEM	—	Finite element model
PVC	—	Plasticized polyvinyl chloride
OT	—	Optical tomography
EQS	—	Electro quasi-static
MQS	—	Magneto quasi-static
2D	—	Two-dimensional
PDE	—	Partial differential equation
kΩ	—	Kilo ohm
pF	—	Pico farad
mA	—	Mili ampere
3D	—	Three-dimensional
MSSIM	—	Multi scale structural similarity
AE	—	Area error
P_{Th}	—	Threshold pre-set value
I-to-V	—	Current-to-voltage
DDS	—	Direct digital synthesizer

AC	—	Alternate-Current
DC	—	Direct Current
GBP	—	Gain Bandwidth Product
ADC	—	Analogue-To-Digital Conversion
PCB	—	Printed Circuit Board
GUI	—	Graphical User Interface
ANOVA	—	Analysis Of Variance
V_{pp}	—	Peak-to-peak voltage

LIST OF SYMBOLS

R	—	Resistance
V	—	Voltage
I	—	Current
σ	—	Electrical conductivity
L	—	Outer diameter pipe
A	—	Area of electrode
G	—	Conductance
D	—	Electric flux density
E	—	Electric field intensity
J	—	Current density
ρ	—	Free charge density
B	—	Magnetic flux density
H	—	Magnetic field intensity
ω	—	Angular frequency
ε	—	Permittivity
μ	—	Permeability
Z	—	Impedance
C	—	Capacitance
f	—	Frequency
IM	—	Independent measurement
N	—	Total sensors
m	—	Mili
d	—	Thickness of non-conducting pipe
d	—	Outer plane thickness
M	—	Sensitivity map
G_T	—	Threshold image

×	—	multiplication
·	—	Scalar multiplication
π	—	Pi (3.142)
+/-	—	Plus or minus sign

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The word 'tomography' comes from the Greek: the term *tomos* means to slice, and *graphein* means to write [1]. The *Oxford English Dictionary* [2] defines tomography as:

> *Radiography in which an image of a predetermined plane in the body or other object is obtained by rotating the detector and the source of radiation in such a way that points outside the plane give a blurred image. Also in extended use, any analogous technique using other forms of radiation.*

Tomography's introduction into the medical field started in the 1950s and led to the possibility of scanning the human body for diagnostic purposes. In medical fields, X-ray tomography was implemented firstly to image the internal human structure (bones) based on the attenuation of X-ray. This radiation-based method allows the medical staff to investigate the internal human structure or the object of interest non-invasively. As a result of this concept of tomography, the technique has become a pioneer for subsequent industrial applications.

Nevertheless, tomography used in the medical field is different from that used in industry, due to the different aims of the applications. Normally, medical tomography is used to determine a specific object in the space, whereas industrial tomography focuses on measuring phase proportions; for instance, the concentration of mediums and the velocity of movement. The development of tomography for industrial applications evolved in the 1980s. Process Industrial Tomography (PIT), known simply as Process Tomography (PT), is a term used for industrial applications. Process tomography has become a promising technique for visualizing and analysing the internal characteristics of process plants in industry applications, such as for two-phase/multiphase flow in pipelines. This PT consists of has many advantages: low cost, non-invasive, non-intrusive, no radiation hazards, and it is suitable for different sized vessels. Thus, process tomography is one of the most important techniques in industrial processes nowadays.

There are three main parts of process tomography: the sensing system; interfacing; and an image reconstruction algorithm for displaying the tomogram, as shown in Figure 1.1. The sensing system includes the sensor, measurement circuits for transmitting and receiving a signal, and signal conditioning circuits to amplify and filter the signal before they are used for the interfacing part. The interfacing part refers to the data acquisition system (DAS). Then, the information from the sensing system about the medium of interest will be used via the DAS in the image reconstruction algorithm for getting and analysing the image of interest, or the 'tomogram'. As a result, the different types of process tomography work based on the different principles of the sensors involved and implemented in the applications.

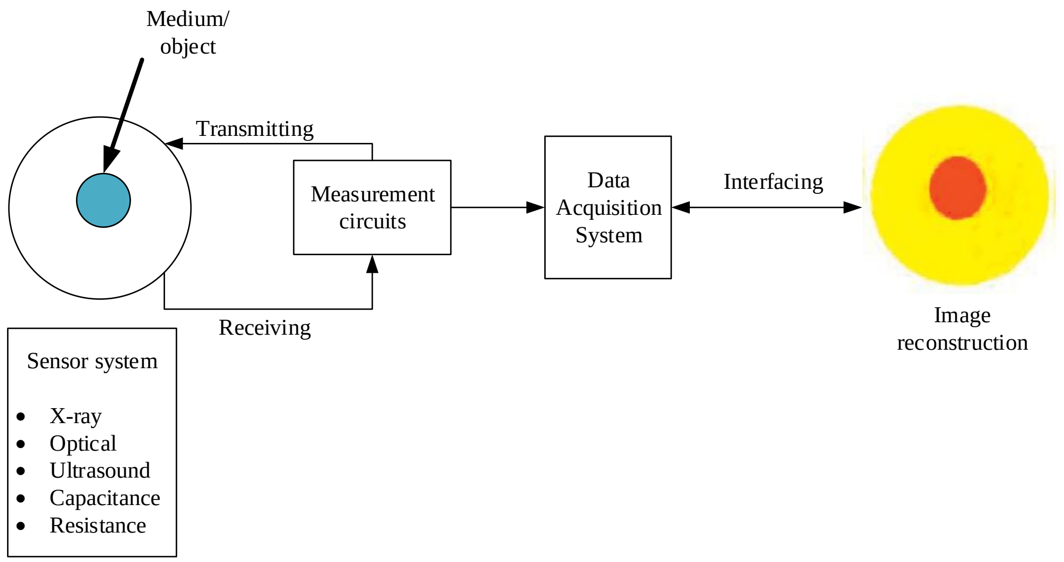


Figure 1.1: General system configuration of process tomography

Tomography can be divided into two fields: hard-field tomography; and soft-field tomography [3]. These classifications of tomography are referred to as the natural behaviour of sensors. Hard-field tomography refers to a condition where the sensitivity of the medium imaged is independent of the distribution of the measured parameters in its whole volume [4]. X-ray tomography, optical tomography, and ultrasonic tomography are examples of hard-field tomography. Soft-field tomography means that the sensitivity of the medium imaged depends on the distribution of the measured parameters in its whole volume [5]. Alternatively, this will cause a challenge in solving the inverse problem of the medium of interest. Electrical tomography can be categorized as a soft-field tomography that includes Electrical Capacitance Tomography (ECT), Electrical Impedance Tomography (EIT) and Electrical Resistance Tomography (ERT).

1.2 Sensing Technique of Process Tomography

Process tomography offers a unique opportunity to reveal the complexities of the internal structure of an object without the need to invade it. There are four types of sensing techniques for tomography: intrusive, non-intrusive, invasive, and non-invasive. The word 'intrusive' is related to how the sensor protrudes into the medium of interest, and 'invasive' means the sensor is applied to the inner surface of the wall of the pipeline. Additionally, the sensing techniques can be combined so that they can be intrusive and invasive, intrusive and non-invasive, non-intrusive and invasive, and non-intrusive and non-invasive as in [6,7]. These concepts are represented in detail in Figure 1.2. However, the non-intrusive and non-invasive is a well-known method applied in industry as it has several advantages. For example, it can avoid the contamination of pure or sterile materials, minimizing the hazards of working with poisonous, radioactive, explosive, flammable or corrosive materials, and decreasing safety and accountancy difficulties with valuable process materials. For this reason, the non-invasive and non-intrusive method is one of the favourite methods applied in process plants compared to other sensing techniques.

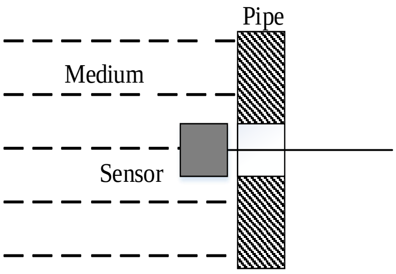
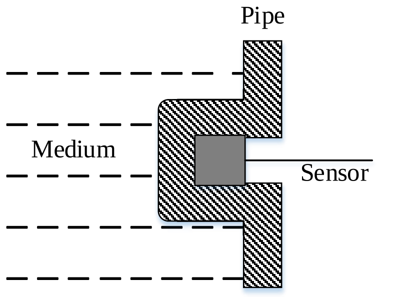
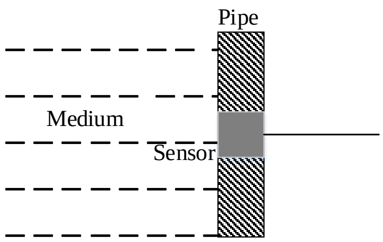
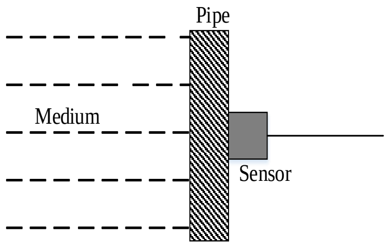
Sensing Technique	Invasive	Non-Invasive
Intrusive		
Non-Intrusive		

Figure 1.2: Types of sensing techniques

1.3 Research Background

A mixture such as liquid–liquid, liquid–solid and liquid–gas two-phase regime is the main concern in process industry applications. The industrial applications involving mixtures, for example, are bubble column, fluidized bed reactor, stirred tank reactor and vertical or horizontal vessel. Visualization of the mixture at an early stage in an industry application may promise good performance and prevent any unwanted conditions during the process. One of the methods that can do this prior visualization is process tomography. Process tomography is used to reconstruct the cross-sectional image of the medium of interest. As it is a non-destructive technique, process tomography has gained wide interest amongst researchers.

Electrical resistance tomography (ERT) is one of the most extensive modalities of process tomography being applied, and has been used in many applications such as in geological surface [8–11], agriculture processes [12,13] and also in industrial processes [14]. The advantages of the ERT application are that it is relatively safe to use and it provides fast response for online and real-time monitoring of the process plant. There are many examples of ERT systems that have been studied, focusing on imaging technique of the liquid–gas, liquid–liquid or liquid–solid mixtures. However, only a few researchers have considered ERT with a non-invasive sensing technique [15–21]. At present, non-invasive process tomography has become a promising imaging technique for monitoring, with potentially enormous applications for mixtures analysis. Therefore, the non-invasive ERT system for measuring and imaging mixtures of a static two-phase regime in a pipeline is proposed for this research.

1.4 Problem Statements

The following are the problems that need to be considered in the design of a non-invasive electrical resistance tomography system for liquid–solid profile measurement.

i. The conventional technique of ERT is applied invasively to the pipeline and causes the metal electrodes to have direct contact with the conductive liquid. The contact between the electrodes and the conductive liquid, such as electrolyte, causes an oxidation to the electrode, also known as an electrochemical erosion effect. This situation leads to electrode corrosion [16].

ii. The current researches into ERT systems produces inconsistency in measurements with unpredictable error [21]. Improper, invasive installation of the electrodes enables the electrodes to produce small bubbles around it when energized by the current signal. Thus, the signal cannot be transmitted and received appropriately.

iii. The use of an invasive ERT system in industrial applications is limited [19]. Limitation of conventional ERT is because the electrodes might affect the nature of the process flow, because the contact between metal electrode and conductive liquid can produce a chemical reaction.

Consequently, the solution to these problems is to use a non-invasive approach, whereby the sensor is clamped to the outside of the pipe wall.

1.5 Aim and Research Objectives

The aim of this research is to design and develop a non-invasive ERT system for a liquid–solid two–phase regime. The objectives of this research are as follows:

i. To design and develop a suitable ERT measurement section using a non-invasive sensing technique, including proposing the suitable excitation frequency and its electronic measurement systems.

ii. To interface the hardware and software for system validation. This validation is demonstrated by the concentration profile computations using online configuration.

iii. To reconstruct the image of a phantom position, using non-invasive ERT system.

1.6 Research Scopes

In developing the non-invasive electrical resistance tomography system to monitor the two-phase regimes of liquid–solid; the scopes of the research will comprise of:

i. The sensor consists of sixteen electrodes that perform as transceiver-sensing operation and clamped on an experimental pipe non-invasively.

ii. Non-invasive ERT development and analysis is conducted on a vertical non-conducting (acrylic) pipe with 100 mm outer diameter and 2 mm wall thickness. The specification of the pipe used in this research does not reflect a vessel applied in industrial applications.

iii. The experimental will be only tested for static flow with tap water and a wooden rod as the conductive liquid and phantom, respectively.

iv. Only one set of measurement data is collected for every experiment conducted in the research. The collection of data is through online configuration.

v. The image reconstruction application is based on existing back-projection algorithms, with no new derivation of an image reconstruction algorithm in this research. The tomogram is reconstructed based on a linear back-projection algorithm through online configuration, and improved using a global thresholding technique through offline configuration.

1.7 Motivation and Contribution

The development of ERT systems in existing studies indicates that most studies have focused on the invasive ERT system. Only several papers have studied the non-invasive ERT system technique [15–21]. However, the presented papers did not particularly discuss hardware designation and development. Therefore, the work in this thesis has thus designed and developed a non-invasive ERT system using 2 MHz frequency that can produce an analysis for multiphase mixtures.

In addition, most of the presented works in the cited literature for ECT and ERT develop the system with a frequency in kHz. At this point, a phase-sensitive demodulation (PSD) method using sophisticated circuit design also needs to be developed in conjunction with the ECT or ERT system, to measure the internal permittivity or internal conductivity. Thus, in this work, it is proven that by developing the non-invasive ERT system with a high frequency level, the PSD technique is not required. The utilization of a high frequency level enables the system to detect the concentration profile of the medium of interest.

Furthermore, corrosion-free electrodes and no contact with the flow in the medium in the non-invasive ERT system introduced a non-invasive conductivity conductor for industry. Thus, it can provide the system with better sensing accuracy.

Moreover, any damage of the sensor occurring in the system can easily be replaced and dealt with in non-invasive ERT. The independent and flexible design of the research enables it to reduce the duration of the troubleshooting process.

1.8 Structure of Thesis

The thesis consists of seven chapters as summarized below:

i. Chapter 1 briefly describes the background of tomography, types of sensing techniques, research background, problem statement, the aim and research objectives, scopes and the study's contribution.

ii. Chapter 2 is the literature review of non-invasive process tomography, current works related the electrical resistance tomography (ERT), the basic principles of non-invasive ERT and also image reconstruction applied in industrial tomography.

iii. Chapter 3 presents the modelling of the non-invasive ERT system that focuses on the optimum frequency source and optimum electrode dimension using COMSOL software.

iv. Chapter 4 discusses solving the forward problem of the system, back-projection algorithm for image reconstruction, the image quality assessment and improving the tomogram using a thresholding technique.

v. Chapter 5 provides details of the hardware and measurement systems, such as the design of electronic measurement circuits, hardware jig and metal sensor, together with the software part of the developed system.

vi. Chapter 6 presents the experiments, results and discussion and compares these with the simulation results. It involves two parts; sensor performance analysis and image reconstructed analysis.

vii. Chapter 7 provides the conclusion to the study and suggestions for future work.

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