SEGMENTED EXCITATION FOR ELECTRICAL CAPACITANCE TOMOGRAPHY

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Specially dedicated to my better half,

Mohd Nurulazmi bin Md Said

and my pillars; Hakim, Hanis and Haziq

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ABSTRACT

Electrical Capacitance Tomography (ECT) system offers a non-invasive measurement for flow properties within pipelines. The resolution of the images can be improved by utilizing more electrodes within the sensing area which causes reduction in size, but this causes low resolution at the center of the reconstructed images due to the limitation of soft field sensors to distribute high electric field to the middle of the pipe. This project studies the performance of using segmented excitation of ECT system in order to overcome low resolution of image reconstruction. The segmented excitation method offers minimum modification of the hardware as it only require changes on the switching configuration. Three different ECT systems (8-electrode, 12-electrode and 16-electrode) are studied via simulation modeling using COMSOL Multiphysics to investigate the distribution of electrical potential and electrical field within the pipeline. Simulation shows 16-electrode ECT system yields the highest potential at the center of the pipe $1.74 \times 10^{-9} V$, as compared to the 8-electrode and 12-electrode for maximum number of excitation, which is half of the total electrodes analysis. For various segmentation excitation with 4-electrode, the adjacent electrode configuration shows 16.6% improvement of electrical potential at the center of the pipe as compared to the opposite excited electrode configuration. The electrical field increases significantly for the segmented excitation as compared to single excitation. The segmented excitation method manages to overcome low resolution problem due to the increased number of excited electrodes. The thesis also describes the process of reconstructing the sensitivity map using COMSOL Multiphysics simulation data. The sensitivity map is reconstructed by extracting raw data and normalization process using standard deviation application. The reconstructed image from the simulation data matches the image reconstructed through the experimental data.

ABSTRAK

Sistem Tomografi Kemuatan Elektrik (ECT) menawarkan pengukuran aliran yang tidak invasif untuk saliran di dalam saluran paip. Resolusi imej boleh diperbaiki dengan memuatkan lebih banyak elektrod di keliling paip dengan saiz yang lebih kecil, tetapi ini akan mengakibatkan resolusi imej di tengah paip menjadi rendah kerana sensor medan lembut tidak dapat mengedarkan medan elektrik yang mencukupi ke bahagian tengah paip. Projek ini mengkaji prestasi pengujaan bersegmen bagi sistem ECT bagi mengatasi resolusi imej yang rendah. Kaedah pengujaan bersegmen menawarkan pengubahsuaian minimum pada peralatan kerana ia hanya perlu mengubah konfigurasi pengujaan bagi meningkatkan resolusi imej yang dijana. Tiga model sistem ECT (8-elektod, 12-elektrod dan 16-elektrod) dikaji secara simulasi dengan menggunakan perisian COMSOL Multiphysics untuk mengkaji agihan potensi elektrik dan medan elektrik di dalam saluran paip. Simulasi menunjukkan 16-elektrod ECT sistem menghasilkan potensi yang tertinggi di tengah paip iaitu 1.74×10^{-9}V, berbanding dengan 8-elektrod dan 12-elektrod bagi analisa bilangan pengujaan maksimum; iaitu separuh daripada jumlah elektrod. Bagi pelbagai pengujaan bersegmen 4-elektrod, konfigurasi elektrod bersebelahan menunjukkan peningkatan potensi elektrik sebanyak 16.6% di tengah paip berbanding dengan konfigurasi elektrod teruja bertentangan. Medan elektrik juga menunjukkan perbezaan yang ketara bagi pengujaan bersegmen berbanding dengan pengujaan tunggal. Kesimpulannya, pengujaan bersegmen dapat menyelesaikan masalah resolusi rendah dengan menambah bilangan elektrod yang diuja. Tesis ini juga menerangkan proses pembinaan semula peta sensitiviti menggunakan data simulasi daripada COMSOL Multiphysics. Peta sensitiviti dijana semula dengan mengekstrak data-data simulasi daripada COMSOL Multiphysics dan proses normalisasi menggunakan aplikasi sisihan piawai. Imej yang dijana semula daripada data simulasi adalah setanding dengan imej yang dibina semula menggunakan data eksperimen.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

°	-	Degree
AC/DC	-	Alternatice Current/ Direct Current
CMOS	-	Complementary Metal Oxide Semiconductor
CT	-	Clinical Tomography
DAS	-	Data Acquisition System
DMT	-	Dual Modality Tomography
ECT	-	Electrical Capacitance Tomography
EIT	-	Electrical Impedance Tomography
EMT	-	Electromagnetic Tomography
ERT	-	Electrical Resistance Tomography
LBP	-	Linear Back Projection
MIT	-	Magnetic Induction Tomography
MRI	-	Magnetic Resonance Imaging
PET	-	Positron Emission Tomography
SNR	-	Signal to Noise Ratio
V	-	Volt(S)

LIST OF SYMBOLS

Q	-	Charge
V	-	Volatge
C	-	Capacitance
$\mathcal{E}_r$	-	Relative static permittivity
$\mathcal{E}_0$	-	Electric constant
d	-	Separation between the plates
$\mathcal{E}_S$	-	Relative permittivity for series model
C_S	-	Capacitance for series model
A	-	Area of cross-section of the electrodes
x	-	Height/length of k level
$\mathcal{E}_P$	-	Relative permittivity for parallel model
C_P	-	Capacitance for parallel model
C_N	-	Normalise capacitance value.
C_{LA}	-	Capacitance measured at higher permittivity
C_{HA}	-	The absolute value of the measured capacitance during the calibration
K_{HA}	-	Pixel permittivity at higher permittivity
K_{LA}	-	Pixel permittivity at lower permittivity
φ	-	Electrical potential
N	-	Number of electrode
M	-	Independent measurement
P	-	Protocol
E	-	Electrical field
F	-	Electrical force
R_1	-	Inner diameter
R_2	-	Outer diameter
ρ	-	Radius ratio
σ	-	Standard deviation
x	-	Each value in the population
K	-	The number of values (the population)

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

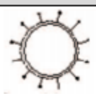
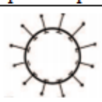
Tomography means as slices of pictures [1]. From The Oxford English Dictionary, Tomography is defined as ‘Radiography in which an image of a predetermined plane in the body or other object is obtained by rotating the detector and the source of radiation in such a way that points outside the plane give a blurred image [2]. Process tomography consists of non-intrusive or intrusive tomographic imaging systems to measure multi-component mixtures in a process vessel or pipeline [1]. For intrusive tomographic technique, the measurement electrode penetrates the pipe wall to obtain the desired signal with direct contact with the flow, whereas for non-intrusive tomographic technique is based on measurement signal from sensors mounted away from the flow. Practically, these sensors are mounted at the periphery of the pipe wall [3]. The system helps to understand the flow distribution inside closed pipe or vessel by detecting the variation of dielectric permittivity [4].

In 1970’s, tomography was applied for medical diagnostic imaging [5]. The article also reported that x-ray imaging was developed in 1980’s to allow scanning internal structure (bones) of human’s body safely and non-invasively. Later, in 1990’s tomography has been progressively developed and it was introduced to manufacturing and processes to inspect closed section including food industry, chemical, petrochemical, food and biochemical industries [6]. The article also reported that the development of tomography in industry is driven by the needs and requirement to inspect the process, to adopt resources efficiently, and to fulfill requirement and for inspection of quality control.

Driven from the demand, the rapid development of tomography is beyond medical applications. There are two types of tomography; electrical tomography method and radiation-based method tomography [7].

Electrical tomography method has gained its popularity more than 10 years ago [7]. Electrical tomography approach suits industrial requirements with detection method and the measurement properties. For instance, resistance tomography is used to determine the distribution of conductivity, capacitance tomography offers detection of different permittivity, and distribution of permeability is detected by inductance tomography. Impedance tomography helps to measure both resistive and reactive components. York [8] also reported that electrical tomography is able to improve profits by reducing process cycle time and waste management. The electrical tomography properties [3] and applications are described in Table 1.1.

Table 1.1: Electrical Tomography application and measurement properties

Method	Typical arrangement	Measure values	Typical material properties	Typical material
ECT	 Capacitive plates	Capacitance C	Permittivity $\varepsilon_r = 10^0$ - 10^2 Conductivity $\kappa = < 10^{-1}$ S/m (low)	oil, deionized water, non metallic powders, polymers burning gasses
ERT (EIT)	 Electrode array	Resistance (Impedance) R/Z	Conductivity $\kappa = 10^{-1} - 10^7$ S/m (wide) Permittivity $\varepsilon_r = 10^0$ - 10^2	Water/saline, biological tissue, rock/ geological material, semiconductors
EMT	 Coil array	Self /mutual Inductance L/M	Conductivity $\kappa = 10^2 - 10^7$ S/m (high) Permeability $\mu_r = 10^0$ - 10^4	Metals, some minerals, magnetic materials ans ionised water

Capacitance tomography is able to detect the variation of permittivity and low conductivity difference which is suitable for non-metallic powders, oils and liquids measurement or medium. The resistance tomography is suitable to detect or measure semiconductors and biological tissues [9].

Another segregation of tomography is the radiation-based method [9]. This method uses infrared, microwave, X rays, gamma rays, neutrons, magnetic resonance, ultrasound or acoustics as the sensor. These methods are quite expensive and required long data collection periods and hence, is not suitable for real-time behavior process monitoring. However, these methods provide high spatial resolution which is more suitable and beneficial for medical measurement and applications.

1.2 Types of Tomography

The determination of the type of sensors used need to consider the purpose of the inspection, the need, the output or the information of the process, as well as the size and environment of the process [1]. The other considerations are depending on the properties or characteristics of the flow material that is being examined and the flow state (gas, liquid, solid) [10]. Process tomography systems are normally classified according to the sensor used.

Ultrasonic imaging tomography is one of radiation-based method and commonly used to visualize body structure including muscles, tendons, vessels, joints, and internal organs. It applies very high wave frequency sound wave to inspect the process. Nowadays ultrasonic imaging is also applied in industrial application [11].

Positron emission tomography (PET) produces a three- dimensional image or picture of body function [12]. The body needs to be emitted indirectly with gamma rays. Images of space inside the body are reconstructed using computer analysis. PET is a Computed Tomography (CT) X-ray is widely used in medical application nowadays.

Electrical Impedance Tomography (EIT) is a medical imaging application which capable of producing three- dimensional images. The conducting electrodes are attached to the skin of the body. Small alternating current is applied to the electrodes which allow it to produce images of the permittivity or conductivity of part of the body's part. The process may be repeated for different current configurations, depends on the measurement needed. The purpose of inspection is to reconstruct image of an internal structure or specific organ [13].

Another type of electrical tomography is Electrical Capacitance Tomography (ECT). ECT applies arrays of electrodes to produce images in closed pipe or vessel. ECT is popular for its simple design, fairly cheap and fast response. ECT system design also allows portability and flexibility in excitation and therefore is the most applied process tomography system in the industry [14]. However, ECT produces low resolution problem due to its soft-field effect.

Magnetic Induction Tomography (MIT) applies by inducing eddy current from excited magnetic coil to produce image electromagnetic properties of an object. This non-destructive test is also known as eddy current tomography, electromagnetic tomography (EMT), eddy current testing and electromagnetic induction tomography [15].

Optical tomography system is an emerging modality as it provides straightforward, inexpensive and has a better dynamic response than other radiation-based tomographic techniques such as x-ray and positron emission tomography. This modality also could perform on high-speed particles due to wide bandwidth coverage [16].

In this project, soft-field sensing Electrical Capacitance Tomography (ECT) is studied. ECT is one of the most widely used tomography system in the industry due to its non-invasive property for flow measurement. The study of ECT in this work resolves the low resolution imaging problem due to soft-field nature of ECT, with minimum modification on the hardware. The proposed idea is to modify the switching method of the electrodes by applying the segmented excitation method.

1.3 Electrode Sensor Installation for ECT

The main sensor used for electrical tomography is based on the sensor installation. The electrodes can be mounted internally or externally of the pipe. It's depends on the material of the pipe wall. If the vessel wall is a non-conducting material, the sensors can be located inside or outside the pipe. On the other hand, if the pipe wall is a conductor, the sensors need to be installed inside the pipe [17]. The configuration of inside and outside the pipe is illustrated in Figure 1.1.

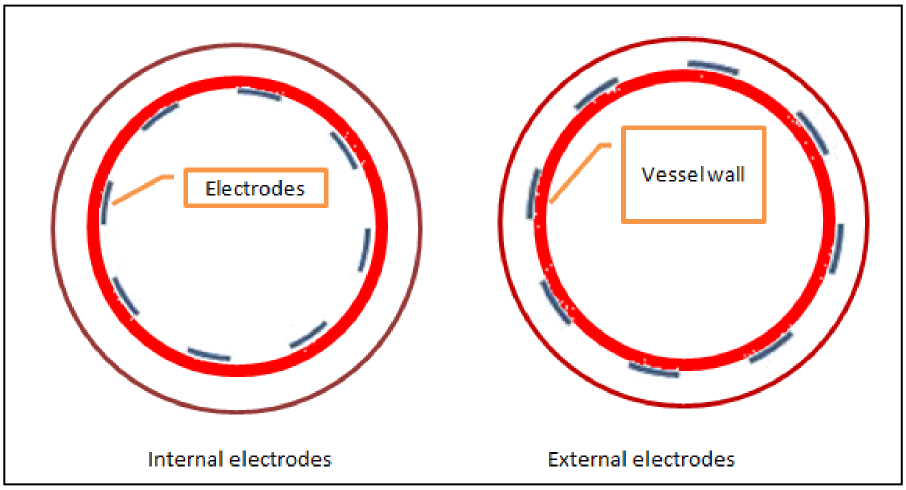


Figure 1.1: Internal and external electrodes installation

External electrodes are non-intrusive and providing simpler design and fabrication procedure. The sensor is not affected by extremely high pressure, temperature and turbulences in the pipe. This method also could avoid any contamination on the electrodes from the fluid or material inside the vessel. However, the external electrode fabrication suffers from the disadvantage of nonlinearity characteristics. The capacitance value varies based on the vessel wall thickness [2]. Practically, the wall thickness is determined by the pressure limitations, usually the wall thickness is between 2 to 4 mm [18].

Differ from external electrodes; internal electrodes need to endure extremely high pressure, temperature and turbulences [18]. Therefore, this installation also requires complex design and more expensive. Another drawback of installing electrodes inside the vessel with corrosive flow material, the electrode surface will be eroded. However, the biggest advantage of internal electrode is it offers linear characteristics. The capacitance value change is directly proportionate with the permittivity change inside the vessel [2].

For ECT, the common installation of sensor is mounted outside the pipe [19, 20]. The sensors do not directly contact with the materials inside the pipe. ECT is a non-invasive and non-intrusive measurement technique. Gamio *et. al.* [21] elaborated the advantages of tomographic images are non-invasive and non-intrusive. The term non-invasive can be described as the system does not disrupt the walls of the pipe wall, for example the installation of the probes. Non-intrusive disturb or distract the process that being tested. ECT has been widely used in many industrial applications such as oil and gas industry, petrochemical, chemical related industry due to its low cost and the flexibility of the design and installation [21]. However, ECT inherits the soft-field nature which contributes to low resolution image reconstruction [22].

1.4 Problem Statement

ECT is a soft-field measurement technique which produced low resolution images [23] at the center of the sensitivity map of tomography. This problem can be solved by increasing the number of electrodes, however, Al-Afeef [22] stated that by increasing the number of electrode, the image quality at the center of pipe will be decreased. The decreasing of image quality is due to the reduction of electrode surface area per unit axial length and the decreasing of inter-electrode capacitances electrodes [17]. Thus, this research studies the feasibility of using the segmented fan-beam excitations projection method to increase the electrical field distribution within the pipeline and subsequently overcome the low resolution problem particularly at the pipe center region.

1.5 Objectives of Research

The main objective of this research is to study the capability of segmented excitation method to improve the resolution of ECT imaging by comparing the electrical potential of the ECT system between single and segmented excitation method. The specific objectives of the research are listed as follows:

1. To investigate the performance of segmented excitation method for improving image resolution, particularly at the center of the pipe.

2. To reconstruct the sensitivity map from simulation of electrical capacitance tomography system for comparing the effectiveness of multiple segmented excitation method.

1.6 Research Scope

In this project, the ECT system is modeled and simulated using numerical modeling method. The model of the ECT system is based on actual existing system in the lab and the designing of ECT will be made using COMSOL Multiphysics 4.0. The main objective of the project is to investigate the pattern distribution of electrical potential and electrical field inside the pipe. Different configuration of segmented excitation was studied to investigate the feasibility of this method to improve the resolution of tomogram images.

1.7 Thesis Structure

This research focuses on the modeling of the ECT system and implementation of segmented multiple excitation to overcome the ECT low resolution problem.

In Chapter 1 – Introduction discusses the introduction of the project. The categorized of tomography is listed and discussed briefly. The research problem and research objective is stated as well as the scope of the project.

Chapter 2 – Literature Review elaborates the ECT system and its applications. The discussion of the model of permittivity and the classifications of tomography modality are stated in this chapter. The advantages and disadvantages as well as the challenges of ECT are described intensively.

Chapter 3 – Characterization evaluation of single versus segmented excitations. The chapter discusses the simulation processes as well as the data processing is discussed. The analysis of the electrical field distribution as well as electrical potential for ECT system models will be presented.

Chapter 4 - Reconstructing of 16-ECT Sensitivity Map. This chapter describes the detail process flow to reconstruct the sensitivity map from simulation data of COMSOL Multiphysics.

Chapter 5 - Conclusion and Future Work. The segmented is expected to produce better result and most importantly, could enhance the image reconstruction of ECT. The recommendation for future work will be described briefly.

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