IMAGE RECONSTRUCTION TECHNIQUE FOR ULTRASONIC TRANSMISSION TOMOGRAPHY

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Dedicated to my beloved family especially my parents, my wife, my lovely daughter Yasaman and my supportive supervisors –Associate Prof. Dr. Sallahuddin Bin Ibrahim, Dr. Mohd Amri Bin Mohd Yunus and Dr. Sayedehsan Alavi Ghahferokhi. Thank you very much for being supportive, helpful and understanding.

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ABSTRACT

Precise flow control has always been a necessity for developing easier approaches or instrumentation for two-phase flow regime. An important method for monitoring this process is called process tomography such as electrical tomography, optical tomography and ultrasonic tomography (UT). In the case of high-acoustic impedance mixtures e.g. bubbly flow, UT has the advantages in monitoring real time data. Although various researches were conducted using UT systems in bubbly flow regimes, there are still weaknesses especially in real time image reconstruction techniques for monitoring the process. Some efforts such as linear back projection (LBP), filter back projection (FBP), convolution back projection (CBP) and iterative techniques are utilized for reconstructing the image with few views data for UT system. Regardless of the utilized method there still exist two main issues in UT image reconstruction both in forward and inverse problems. In the case of forward problem, the gaps between sensitivity maps cause artifacts in a reconstructed image. Moreover, for inverse problem, limited number of sensors causes artifacts in reconstructed image. In the case of high noisy environment, the LBP, FBP and CBP methods are not capable of totally removing the noise and artifacts level. Dynamic motion of flow regime is considered as another issue in UT system which causes inaccuracy in image reconstruction. Therefore, these issues were considered in developing a modified image reconstruction algorithm which was based on improving the CBP algorithm both in forward and inverse problems. A modified sensitivity map based on Gaussian distribution was utilized to combat the gaps in forward problem, and for the case of inverse problem, the wavelet fusion technique was applied to reduce the noise level, artifacts and the effects of dynamic motions. The simulation and the experimental works had been conducted based on different static profiles. Various types of image reconstruction algorithms were implemented and compared with the proposed technique. The quality of the final reconstructed images was evaluated using structural similarity (SSIM) and peak signal to noise ratio (PSNR). Results show that the WCBP outperforms LBP and CBP in case of SSIM and PSNR. Comparing to LBP, the SSIM and PSNR were improved at least by 30% and 5% respectively while for CBP the improvement were about 5% and 1% respectively.

ABSTRAK

Kawalan aliran jitu sentiasa menjadi satu keperluan untuk membangunkan pendekatan yang lebih mudah atau peralatan untuk rejim aliran dua fasa. Satu kaedah penting bagi memantau proses ini dipanggil proses tomografi seperti tomografi elektrik, optik dan ultrasonik (UT). Dalam kes campuran galangan akustik tinggi contohnya aliran berbuih, UT mempunyai kelebihan dalam memantau data masa sebenar. Walaupun pelbagai kajian telah dijalankan menggunakan sistem UT dalam rejim aliran berbuih, masih terdapat kelemahan terutama dalam teknik-teknik pembinaan semula imej masa sebenar untuk memantau proses. Beberapa algoritma seperti unjuran belakang lelurus (LBP), unjuran belakang bertapis (FBP) dan teknik lelaran digunakan untuk membina semula imej dengan beberapa paparan data untuk sistem UT. Tidak kira apa kaedah yang digunakan, masih terdapat dua isu utama dalam pembinaan semula imej UT dalan kedua-dua masalah hadapan dan songsang. Jurang dalam peta sensitiviti mempunyai kesan negatif ke atas imej yang dibina semula dalam kes masalah hadapan. Selain itu, untuk masalah songsang jumlah penderia yang terhad menyebabkan artifak dalam imej yang dibina semula. Dalam kes persekitaran yang amat hingar, kaedah LBP, FBP dan CBP mampu mengenepikan sepenuhnya tahap hingar dan artifak itu. Gerakan dinamik rejim aliran dianggap sebagai isu lain dalam sistem UT yang menyebabkan ketidaktepatan dalam pembinaan semula imej. Oleh itu, isu-isu tersebut telah diambil kira dalam mengubah suai algoritma pembinaan semula imej yang bertujuan memperbaiki algoritma CBP dalam masalah hadapan dan songsang. Sebuah peta kepekaan yang telah diubah suai berasaskan taburan Gaussian digunakan untuk mengatasi jurang yang wujud dalam masalah hadapan dan bagi kes masalah songsang teknik pelakuran gelombang kecil digunakan untuk mengurangkan tahap hingar, artifak dan kesan gerakan dinamik. Simulasi dan ujikaji telah dijalankan dalam profil statik yang berbeza. Pelbagai jenis algoritma pembinaan semula imej telah dilaksanakan dan dibandingkan dengan teknik yang dibentangkan. Kualiti imej akhir yang dibina semula dinilai dengan menggunakan persamaan struktur (SSIM) dan nisbah isyarat puncak kepada bunyi (PSNR). Keputusan menunjukkan keunggulan kaedah WCBP berbanding dengan LBP dan CBP untuk SSIM dan PSNR. Berbanding dengan LBP, SSIM dan PSNR telah diperbaiki sekurang-kurangnya masing-masing 30% dan 5% manakala untuk CBP, perbaikannya ialah masing-masing 5% dan 1%.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACM	-	Adjacent Criterion Method
CBP	-	Convolution Back Projection
CT	-	Computed Tomography
DWT	-	Discrete Wavelet Transform
ECT	-	Electrical Capacitance Tomography
EIT	-	Electrical Impedance Tomography
ERT	-	Electrical Resistance Tomography
FBP	-	Filtered Back Projection
FEM	-	Finite Element Method
HIS	-	Hue Intensity Saturation
IF	-	Image Fusion
LBP	-	Linear Back Projection
MRT	-	Magnetic Resonance Tomography
MSE	-	Mean Squared Error
NDT	-	Nondestructive Testing
OT	-	Optical Tomography
PET	-	Positron Emission Tomography
PCA	-	Principal Component Analysis
PT	-	Process Tomography
SART	-	Simultaneous Algebraic Reconstruction Technique
SIRT	-	Simultaneous Iterative Reconstruction Technique
SNR	-	Signal to Noise Ratio
SSIM	-	Structural Similarity Index
UTT	-	Ultrasonic Transmission Tomography
UT	-	Ultrasonic Tomography
VF	-	Void Fraction
WCBP	-	Wavelet based Convolution Back Projection

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Multi-phase flow takes place as two or more discrete phases flow in a closed pipe or a vessel. Examples of phases include gas, liquid or solid and also different immiscible liquids or solids [1]. Two phase flow of fluids (e.g. gas/liquid, liquid/liquid, etc.) is an important phenomenon in which two immiscible phases coexist in a thermodynamic equilibrium. As a two phase flow regime, bubbly flow column are intensively used as multiphase contactors and reactors in chemical, biochemical and petrochemical industries. Investigation of design parameters characterizing the operation and transport phenomena of bubble columns have led to better understanding of the hydrodynamic properties, heat and mass transfer mechanisms and flow regime characteristics ongoing during the operation [2, 3]. Due to the stringent regulations on precise flow control especially in the case of two phase fluid flow,, there has always been a necessity for developing an easier to use, yet more precise approaches or instrumentation. Accordingly, tomographic measurement is more significant and attractable especially in today's industrial process [4].

Process tomography (PT) provides a novel tool for visualizing the internal behavior of industrial processes. PT which has been applied to various industries is a versatile technique for producing cross-sectional images of a continuum with the ability of discerning between the compartments of a heterogeneous phase from the continuous one [3]. These images provide valuable information on a process, which are applicable in monitoring, mathematical model verification and also intelligent control. In PT the interest is often in extracting valuable information, such as void fraction (VF), mean velocity. [5]. This information which is provided by processing the signals received at multiple locations enables the researchers to acquire a global knowledge of the measured field.

Since 1980 there have been some efforts to develop the industrial PT techniques. Electrical capacitance tomography (ECT), electrical impedance tomography (EIT), electrical charge tomography (ECHT), optical tomography (OT), Gamma-ray, X-ray, magnetic resonance imaging (MRI) and ultrasonic tomography (UT) are examples of these techniques which are applied in PT based on the inherent properties of materials [6]. These methods can be categorized as hard-field and soft-field which in the former case regardless of the type of material or medium, the direction of travel of the energy waves from the source is constant. UT and X-ray are two examples of hard-field tomography. On the other hand, in the soft-field, the electric current is introduced to the medium being imaged and an electric field distribution is determined based on the physical electrical properties of that material, allowing a map of resistance, capacitance or impedance distribution to be reconstructed by a computer to form the tomogram. The nature of soft field is much more complex than hard field and requires considerably more computer analysis and algorithms to reconstruct the image [7] because soft field is a nonlinear process while hard field is a linear one. ECT is an example of soft-field tomography.

Among all these methods, ultrasound is able to detect changes in acoustic impedance (Z), which is closely related to the density (ρ) of the media ($Z = \rho c$, where c is the velocity of sound), and thus complements other tomographic imaging technologies such as ECT and EIT [8]. Therefore, UT imaging can be used in liquid/gas two-phase flow regime with two-component high-acoustic impedance mixtures e.g. bubbly flow[9]. Moreover, it is low in cost compared to X-ray or Gamma-ray methods [10].

UT consists of two parts; hardware and software. Hardware includes the sensing array which is mounted peripherally around the pipe, electrical circuits including signal conditioning and controllers as well as a PC for data processing and monitoring. After exciting a sensor with an electrical pulse, physical waves will propagate from the ultrasonic sensor towards the medium. The propagated waves inside the pipe are scattered and attenuated while they encountered with a wall of two materials. Therefore, a wave with a weak amplitude can be sensed by the receivers mounted on the other side of the pipe. After collecting the data from all receivers, the next step is to feed these data to a PC in order to reconstruct an image which represent the profile of the materials inside the pipe cross section. This procedure is called the image reconstruction technique.

The software consists of image reconstruction algorithms which plays an important role in the last step of cross-sectional monitoring of a pipe. Image reconstruction consists of two parts namely forward and inverse problem. The forward problem deals with the theoretical output of each sensor and the sensing area using sensitivity maps while the objective of the inverse problem is to reconstruct an image to find the distribution of materials such as gas bubbles inside water.

There are two major categories in the field of image reconstruction methods; analytical/single step and series expansion/iterative methods [11]. Beside these two major categories there are some heuristic methods which have been used for image reconstruction including non-linear, artificial neural network (ANN) [12, 13] and fusion methods (wavelet fusion) [14, 15], where a dual mode tomography is applied. Contrary to the speed and simple implementation of analytical methods, they have limitations in terms of the less number of sensors being used or few view data, which leads to less accuracy. On the other hand, iterative methods are insensitive to noise and they are capable of reconstructing an optimal image in the case of incomplete data but they suffered mostly from low computational speed [16].

There have been some attempts to improve the setup of ultrasonic hardware for two-phase flow measurement as reported in [17-22]. They deal with different ultrasonic frequencies, various numbers of sensors, different types of sensors and speeding up the data acquisition systems to enhance the resulting image. Apart from hardware setup, some efforts have been made on utilizing new techniques for improving the reconstructed image in UT. These image reconstruction techniques mostly use analytical methods such as linear back projection and filter back projection to reconstruct an image from projections [23-25]. The high speed of analytical methods which is a critical point in real-time processing is the main reason in selecting them rather than the iterative methods. However, the drawback of the analytical methods is that they do not generate an optimal quality image in the case of incomplete data.

In UT, the limited number of sensors yields incomplete data which leads to artifacts and noise in images reconstructed using the analytical method. Therefore, in this case the VF which depends on the quality of the reconstructed images in UT is also poor. It should be noted, in industrial process data obtained from VF is used to calculate some parameters of materials which is very important and critical for measurement analysis [26, 27]. In order to improve the VF parameter for reconstructed image, this thesis focuses on developing an image reconstruction algorithm based on an analytical method for ultrasonic transmission mode tomography (UTT) system. To this end, for the forward problem a new sensitivity map is developed to improve the quality of the reconstructed image and in the inverse problem the wavelet fusion is utilized to reduce noise which appears in the image.

1.2 Problem Formulation

Some efforts utilizing linear back projection (LBP) [28], filter back projection (FBP) [29] and algebraic reconstruction techniques [30] have been employed for reconstructing images with few views of data for the UTT system. Regardless of the utilized method there still exist two main issues in UTT image reconstruction both in forward and inverse problems. The subsequent subsections will briefly describe these issues.

1.2.1 Forward Problem

Figures 1.1(a) to (d) illustrates the 2-D phantom of three air bubbles in liquid as well as its reconstructed images with LBP method using different sensitivity maps. The images were reconstructed by considering 16-sensors mounted around the cross section of a pipe. Figure 1.1 (b) shows the sensitivity maps generated with respect to the physical length and position of sensors (S1-S16). Figure 1.1 (c) is the reconstructed image by the LBP method using the sensitivity maps with gaps. Finally, Figure 1.1(d) is reconstructed using a sensitivity map without gaps. By comparing Figures 1.1 (c) and (d) it can be concluded that the reconstructed image by modified sensitivity maps improve the quality of images.

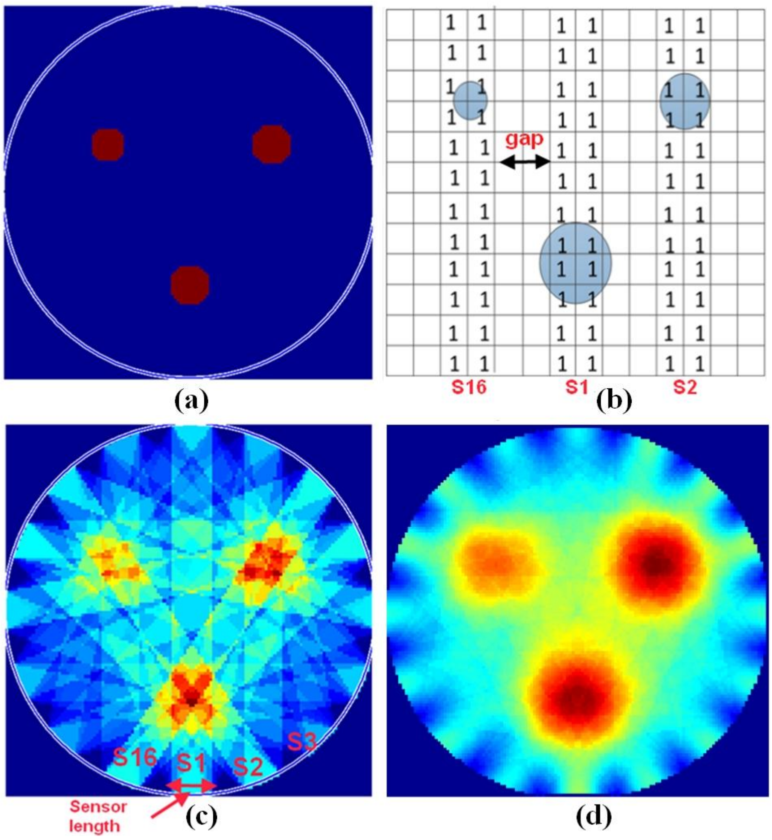

Figure 1.1 (a) Phantom simulated in MATLAB (b) sensitivity map of S16-S1-S2 sensors in 2-D view (c)) Image reconstructed by LBP method with gaps in sensitivity maps (d) Image reconstructed by LBP method using sensitivity maps without gap

In order to reduce the effect caused by gaps, [23] virtually considered the length of the sensors twice than the physical length and used an equation based on the inclusion of each pixel with the line between excited transmitter and receiver. Even this method had covered the gaps but doubling the length of sensors would result to increase the detectable size of bubbles as well, therefore, the error rate is still high.

1.2.2 Inverse Problem

Because of the high accuracy of the iterative methods they have been utilized for offline processing, but their accuracy suffered due to the slow processing speed in real-time applications [31]. Hence, the analytical method is the best choice for the UT system.

Based on the physical aspects of the ultrasonic wave propagation which depends on the properties of the medium, the obtained images from the analytical methods are noisy and include artifacts. A four bubbles phantom in Figure 1.2 (a) simulated in MATLAB and its reconstructed images by the LBP and FBP methods in Figures 1.2 (b) and (c) shows an example of such noisy images. In the case of high noisy environment the LBP and FBP methods are not capable of totally removing the noise and artifacts level as shown in Figures 1.2 (b) and (c).

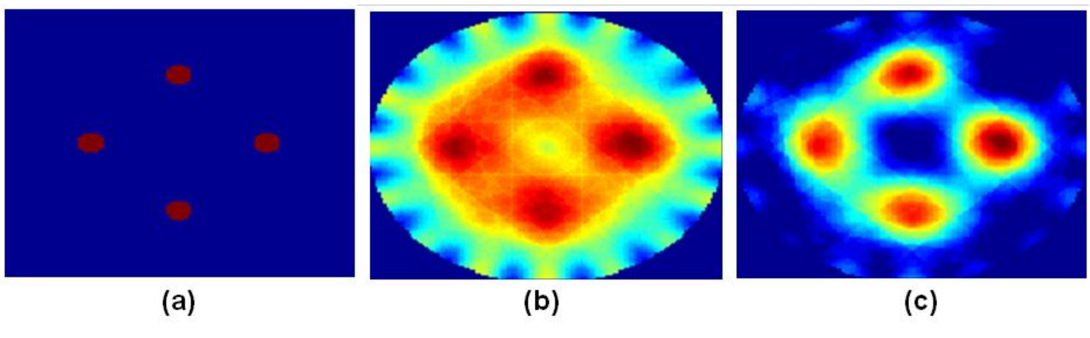

Figure 1.2 (a) Phantom simulated in MATLAB (b) Noisy image reconstructed by the LBP method (c) Noisy image reconstructed by the FBP method

The dynamic motion of flow regime is considered as another issue in the UT system which causes inaccuracy in image reconstruction. In a vertical pipe, the bubble shape and its velocity is changed during movement from the bottom to top which effects on temporal and spatial resolution. High frequency is needed to achieve higher spatial resolution. As an example, the spatial resolution of a system using array of 333 kHz ultrasonic sensors should be 2.25% of a pipe with inner diameter of 100 mm [32], but conventional method e.g. LBP and CBP reconstruct images with low spatial resolution.

1.3 Objectives of Study

A limited number of sensors in UTT system cause difficulties in two-phase flow regimes image reconstruction such as creating gaps in the resulting image. The presence of noise, which commonly occurs in industrial processes, lead to additional problems. In this research a method is proposed to improve image reconstruction using a limited number of sensors in UTT system.

According to the stated problems, the main objectives of this thesis are as follows:

(i) To develop an image reconstruction technique based on the analytical method in both forward and inverse problems for two-phase flow regimes inside a vertical pipe using the UT system.
(ii) To implement a real 16-channel UT system for bubbly flow regime by transceivers sensors.
(iii) To validate the accuracy of modified method results using different image quality criterions.

1.4 Scope of the Study

The research scopes of this thesis consist of the following parts:

- To study image reconstruction principles and methods employed in UTT system i.e. LBP, algebraic reconstruction techniques (ART), and CBP and image fusion techniques based on the wavelet transform.
- To simulate bubbly flow regime in MATLAB software for image reconstruction techniques and accessed the performance of proposed image reconstruction algorithms.
- To implement an experimental UTT setup with transceiver sensors for image reconstruction validity.

1.5 Thesis Layout

The organization of this thesis is structured as follows:

In the first chapter of the thesis an overview of process tomography is presented and the existing problems in the theory of image reconstruction by UTT system are elaborated. Based on the formulated problems the objectives and scopes of the thesis have been defined.

Chapter 2 presents a literature review on tomography including ultrasonic tomography system. While, some important related works in this area were critically reviewed and deeply scrutinized, current challenging problems facing each image reconstruction method are also discussed.

Chapter 3 provides the proposed methods to improve the image reconstruction technique for UTT systems in both forward and inverse problems and also presents a new technique to combat the noise effects in image reconstruction.

Chapter 4 describes the proposed technique using software simulation in MATLAB. The analytical formulation of the new technique is also presented in this chapter.

The proposed technique is experimentally verified and the results are presented in chapter 5. Chapter 5 also discusses the system performance and the comparison was made with other research works in this scope.

Finally, the research contributions, conclusions and future work as well as project constraints and limitations are discussed and presented in chapter 6.

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