NON-INVASIVE IMAGING OF LIQUID/GAS FLOW USING ULTRASONIC TRANSMISSION-MODE TOMOGRAPHY

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Dengan nama Allah yang Maha Pemurah lagi Maha Pengasih.

To my beloved and supportive parents,

Norkharziana Mohd Nayan,

brothers and sisters.

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ABSTRACT

Real-time process monitoring plays a dominant role in many areas of industry and scientific research concerning liquid/gas two-phase flow. It is proved that the operation efficiency of a process is closely related to accurate measurement and control of hydrodynamic parameters such as flow regime and flow rate. The ultrasonic tomography which has been developed recently for the liquid/gas visualization mostly implements the invasive systems. The invasive systems however could not withstand high pressure from the industrial pipeline besides it has a few disadvantages and limitations. Due to the disadvantages and the limitations of an invasive system therefore this thesis presents a non-invasive of ultrasonic tomography system to overcome the problems. By using 16-pairs of ultrasonic transducers, the electronic measurement circuits, the data acquisition system and suitable image reconstruction algorithms, the online measurement of a liquid/gas flow was realized. The system was capable of visualizing the internal characteristics of liquid and gas flow and provides the concentration profile for the corresponding liquid and gas flow. The results obtained are useful for the online monitoring of liquid/gas flow in flow regime, chemical mixture transportation or fluid transportation at sub-sea oil fields.

ABSTRAK

Proses pemerhatian masa nyata berkenaan dengan pengaliran cecair/gas dalam dua fasa memainkan peranan yang penting dalam pelbagai cabang industri dan penyelidikan saintifik. Telah terbukti bahawa kecekapan operasi bagi sesuatu proses adalah bergantung kepada ketepatan pengukuran dan pengawalan ke atas parameter hidrodinamik seperti regim aliran dan kadar aliran. Tomografi ultrasonik yang telah di rekabentuk pada masa kini bagi pemerhatian cecair/gas kebanyakannya mengunakan sistem bersentuhan. Bagaimanapun, sistem ini tidak mampu bertahan dengan tekanan yang tinggi yang terdapat dalam salur perpaipan industri di samping ia mempunyai beberapa keburukan dan juga terbatas kepada had-had tertentu. Kesan ke atas keburukan dan pengehadan ini telah membawa kepada rekabentuk sebuah sistem yang tidak menggangu proses aliran seperti matlamat dalam tesis ini. Dengan menggunakan 16-pasang penderia ultrasonik, sistem pengukuran elektronik, sistem perolehan data dan algorithma pembentukan imej yang bersesuaian, pengukuran masa nyata bagi aliran cecair/gas dapat direalisasikan. Sistem ini dapat memaparkan ciri-ciri dalaman bagi aliran cecair/gas dan memberikan profil ketumpatan bagi aliran cecair/gas tersebut. Keputusan yang diperolehi berguna bagi pemerhatian masa nyata aliran cecair/gas bagi regim aliran, penghantaran campuran bahan kimia atau penghantaran cecair di kawasan luar pantai.

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LIST OF ABBREVIATIONS

$\overline{M}_{Tx,Rx}(x, y)$	-	Normalized sensitivity map for the view of Tx to Rx
AC	-	Alternative Current
A_d	-	Annular test pipe diameter
ADC	-	Analog to Digital Converter
AE	-	Area Error
A_G	-	Gas area percentage
A_L	-	Liquid area percentage
ART	-	Algebraic Reconstruction Technique
$B_{x,y}(m,n)$	-	Boolean array used to represent the pixels
c	-	Sound Velocity
D	-	Transmission Coefficient
DAS	-	Data Acquisition System
dB	-	Decibel
ECT	-	Electrical Capacitance Tomography
EIT	-	Electrical Impedance Tomography
F	-	Frequency
GUI	-	Graphical User Interface
HBRA	-	Hybrid Binary Reconstruction Algorithm
HRA	-	Hybrid Reconstruction Algorithm
Hz	-	Hertz
IC	-	Integrated Circuit
kHz	-	Kilohertz
LBPA	-	Linear Back Projection Algorithm
LED	-	Light Emitting Diode
MHz	-	MegaHertz
$M_{Tx,Rx}(x,y)$	-	Sensitivity map for the view of Tx to Rx

$N(x,y)$	-	Sum of sensitivity maps
NMR	-	Nuclear Magnetic Resonance
PC	-	Personal Computer
PCB	-	Printed Circuit Board
p_d	-	Transmitted Wave Sound Pressure
p_e	-	Incident Wave Sound Pressure
PET	-	Positron Emission Tomography
PIV	-	Particle Image Velocimetry
p_r	-	Reflected Wave Sound Pressure
PSV	-	Particle Streak Velocimetry
P_{th}	-	Threshold pixel
PTV	-	Particle Tracking Velocimetry
R	-	Reflection Coefficient
Rx	-	Ultrasonic Receiver
S_d	-	Transducer Diameter
SMD	-	Surface Mount Device
$S_{Tx,Rx}$	-	Sensor Loss Voltage
TOF	-	Time-Of-Flight
t_s	-	Observation Time
Tx	-	Ultrasonic Transmitter
v	-	speed of sound
$V_{ref\ Tx,Rx}$	-	Reference voltage by ultrasonic receiver during full liquid flow
V_{th}	-	Threshold voltage
$V_{Tx,Rx}$	-	Ultrasonic receiver voltage (sensor value)
Z	-	Acoustic Impedance
α	-	Ultrasound Divergence Angle
β_s	-	Liquid component fraction
λ	-	Wavelength
ρ	-	Density

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CHAPTER 1

SIGNIFICANCE OF THE STUDY

The word "tomography" is derived from Greek language, "Tomoυ" means cutting section and "Graph" means picture. Tomography is a field of interdisciplinary that is concerned with obtaining cross-sectional images of an object. Therefore, the tomography process can be defined as a process of obtaining plane section images of an object (Williams and Beck, 1995).

Measuring techniques capable of monitoring continuously and simultaneously the dynamics of the liquid flow without interfering the hydrodynamic condition in the system are required to elucidate the transient phenomena in such multiphase systems. Unfortunately, such techniques are very limited.

The tomography was first applied in industrial field in middle of 1980's. The tomography process can increase the productivity and the efficiency of a process that uses material transportation through pipes such as in oil industry. Pipes flow visualization is often to be the first step in experimental analysis in order to improve the pipe flows and performs the process control. This makes the tomographic measurement becomes more important in industrial process nowadays (Williams and Beck, 1995).

A simple tomography system can be built by mounting a number of sensors around the circumference of a vertical pipe or horizontal pipe. The output signal from the sensors will be sent to the computer via an interface card. The computer will receive the signal from the respective sensors to perform data processing and finally construct a cross-section flow image in the pipe.

Process tomography is a technique still in its infancy, but it has the potential for enabling great improvements in efficiency and safety in process industries, while minimizing waste and pollution in a range of applications. It can be used to obtain both qualitative and quantitative data needed in modelling a multi-fluid flow system. In tomography, multiple projections are used to obtain sets of data from various views across the process vessel. These data are used to provide tomographic images representing the contents of the pipeline or vessel. The tomographic imaging of objects provides an opportunity to unravel the complexities of structure without invading the object (Dyakowski, 1995).

Information obtained from tomography will enable concentration, velocity and flow-rate to be determined over a wide range of flow regimes by providing better averaging in time and space through multi-projections of the same observation (Abdul Rahim, 1996). Tomography will provide an increase in the quantity and quality of information when compared to many earlier measurement techniques (Abdul Rahim, 1996).

1.1 Background Problems

In the previous research conducted by Gai *et al.* (1989b), the non-invasive of ultrasonic tomography fabrication technique was introduced. Since then, the improvement on the research work is no longer carried out. Later, the development on ultrasonic tomography has focused more to liquid/gas two-phase flow (Xu *et al.*, 1993; Xu and Xu, 1997; Xu *et al.*, 1997). However, the latter system implements invasive technique which is not favoured mostly by the industries. Besides, the system constructed by Xu *et al.* (1997) utilized high excitation voltage (200V) for the

transmitter. This is quite dangerous if any fault happened to be in the system. Nevertheless, the high excitation voltage has put a restriction on the system and also the application.

1.2 Problem Statements

The approach that will be used in this research is a non-invasive technique where 16 pair of ultrasonic transducers will be mounted on the surface of an acrylic pipe. The ideas involved in considering the method of non-invasive technique and developing the real-time image reconstruction are listed as follows:

- By using the ultrasonic method in air is very inefficient due to the mismatch of the sensors' impedance as compared with the air's acoustic impedance (Abdul Rahim *et al.*, 2003). New types of sensor are continually being developed but the effective ones are expensive. Thus, an acoustic coupling should be equipped between the sensors and the outer pipe surface so that the ultrasonic pulses could through the pipe. In addition, the assumption of straight-line propagation of ultrasonic waves has been used.

- The selection of ultrasonic transducer must be suitable to the application design where the transducer projection should be in a wide angle. This is important for successful implementation of fan-shaped beam projection technique. Besides, it should compromise with the low excitation voltage of ultrasonic transmitter. This is to ensure the system design safety.

- Supplying pulses to activate the transmitting sensors should ideally be software controlled so that the timing of the pulses can be easily varied and the synchronization is ensured. Besides, the pulses to activate the transmitter should be long enough for the transient response and it is short enough to avoid multiple reflection and overlapping receiver signals. Thus, the microcontroller is needed for controlling those.

- A low-noise signal conditioning circuit is required to amplify and process the ultrasound receiver signal. In ultrasonic tomography system, the noise has become the most challenging issue. This is because the ultrasound information is relying on the received signals by the receiver. Therefore, noise existence has become the most significant disturbance.

- The cross-sectional distribution of the physical property is obtained by reconstruction of the integral values of the property field projected (measured) from different directions. There are numerous reconstruction algorithms (Natterer, 1986) are available for tomographic reconstruction and the suitable algorithm is selected to perform the real-time image reconstruction.

1.3 Importance of Study

Fluid flows are widespread in the oil industry, chemical plant, energy and biological engineering, where the operating efficiency of such process is closely concerned with the flow regime (Fordham *et al.*, 1999). The operating conditions in a fluid flow for various applications may vary widely. For example, the pressure can vary from as low as a few bars in liquid transportation, to as high as up to 1000 bar in slurry conveying operations. Characteristics of the fluids may range from clean water to highly abrasive cement slurries, viscous gel suspensions or erosive and dangerous chemical solutions. In such conditions, accurate measurement and on-line monitoring of processes are extremely difficult (Hou *et al.*, 1999).

An offshore oil production platform produces oil, water, gas and sediment in the form of a suspended multiphase mixture (Southern and Deloughry, 1993). This mixture is fed into oil separation vessels to recover the oil and gas. Water and sediment are removed and can be returned to the environment when there is a minimum of oil contamination. This ensures maximum extraction of the oil and minimum pollution of the environment (Southern and Deloughry, 1993). It is important that the sampling method employed for measuring the percentage of water

contained in the crude oil be as accurate as possible in order to optimize oil production and separation. This will reduce the operating cost and enable early detection of faults in the process (Xu *et al.*, 2001).

For measuring flow rate, the flow meters which are available currently cannot operate independently in the fluid flow (Hou *et al.*, 1999). Most of the flow meters require a homogeneous mixture of components in order to obtain measurement stability and the required accuracy especially in horizontal pipes (Yan *et al.*, 2004). The performance of turbine flow meters can be seriously affected by the viscosity changes and the presence of solid particles in the flow. Similar degradation also happens when differential pressure instruments are used (Hou *et al.*, 1999). Electromagnetic flow meters which are widely applied cannot be operated if the conductivity of the fluid drops below 10^{-4} S/m (Ahn *et al.*, 2003). As most sensors currently used in multiphase flow meters are affected by the distribution of components in the mixture, tomographic imaging may possibly improve the accuracy and provides a wider measurement range.

1.4   Aims and Objectives of the Thesis

The main objective of this research is to develop a non-invasive ultrasonic tomography with real-time liquid visualization application program for measuring the liquid/gas two-phase flow. It is carried out by employing 16-pairs of ultrasound transducer as the measuring device, supported by the electronic circuitry system and the data acquisition system and also the application software for image reconstruction. The specific objectives of this thesis are:

1. To review the process tomography techniques especially in ultrasonic tomography system and the image reconstruction principles.
2. To implement ultrasonic transducers non-invasively in imaging process for determining the cross-section of liquid and gas flow in a process vessel.
3. To investigate the suitable ultrasonic transducer for non-invasive application, the transducer fabrication techniques and the suitable acoustic coupling.

4. To design and implement the electronic measurement system for Ultrasonic Tomography imaging in liquid/gas flow.

5. To implement microcontroller for controlling ultrasound projection, signal conditioning circuit triggering, the operation and synchronization of data acquisition system.

6. To develop an application program for reconstructing the concentration profile of liquid/gas two-phase flow regime and detect the sludge existence in the process vessel by using Visual Basic 6.0 software.

7. To implement suitable algorithms for the image reconstruction.

8. To interface the hardware and software system using a suitable interfacing card for real-time image processing.

9. To provide suggestions for future expansions and improvements on this research.

1.5   Research scopes

The research scopes are divided into six main parts. They are the transducers fixture design, the coupling material, the electronic measurement circuit, the digital controller and the data acquisition system, the application program for performing the image reconstruction and finally the thesis writing. The details are explained as following:

i.   The transducers fixture design

The design includes the mechanical structure of the fixture, the transducers arrangement geometry, the transducer's beam angle, the non-invasive transducer fabrication technique and the cost effective to the design.

ii.   Transducers coupling material

The design includes the selection of couplant that is suitable with the experimental environment and the handling feasibility.

iii.   The electronic measurement circuit

The design includes the ultrasound signal generator, the selection of low-noise amplifier integrated circuit (IC) and the appropriate amplifying technique, the signal processing circuit using the sample and hold technique and other electronic design. At the same time, the printed circuit board (PCB) layout and the electronic components positioning are took into consideration to reduce the noise within the circuits.

iv.   The digital controller and the data acquisition system

The design includes the microcontroller design, the ultrasound projection sequence, the receiver reverberation delay estimation, the determination of observation time (t_s), the sample and hold triggering signal and finally the synchronization of data acquisition by controlling the data acquisition system (DAS) start and stop operation.

v.   The application program for performing the image reconstruction

The design includes the data acquisition configurations (sampling rate, gain, operation mode, input range, number of samples, start and stop operation method, memory storage and the data transferring method), the liquid and gas measurement, the transducers output modelling, the forward problem solution, the graphical user interface (GUI), the implementation of image reconstruction algorithm and the tomogram.

vi.   The thesis writing

1.6   Organization of the Thesis

Chapter 1 presents an introduction to process tomography, the research background problems, the problem statements and the importance of the study, the research objectives and the research scopes.

Chapter 2 describes an overview on process tomography, common types of tomography sensor and the tomographic technique, some literature review regarding the ultrasonic tomography including the principles, the limitation and the recent research on it.

Chapter 3 explains the modelling and some investigation on the ultrasonic tomography system. The process of obtaining sensitivity maps were details and the image reconstruction algorithm for the system were briefly summarized. Finally, the error measurement analysis for the system was introduced.

Chapter 4 discusses the design of ultrasonic tomography system including the hardware and software development and also the flow model.

Chapter 5 presents the results obtained by the system where some experiments were carried out to investigate the capability of the system. The experiments show the results obtained for a range of liquid volume represented by several test profiles.

Chapter 6 was to discuss the conclusions and the suggestions for the overall system design.

Therefore, investigation of using the non-invasive Ultrasonic Tomography on the metallic vessel is recommended.

(v) Image processing time obtained for the current system is about 0.4 second (for 64x64 pixels tomogram). However, for successful real-time monitoring, the processing time should be faster. This can be done on a higher computer speed such as the Pentium IV computer. It is expected that the image processing time will greatly improved by using this computer.

(vi) Converting the current application program into the Visual C++ platform is believed could increase the image reconstruction speed. It is because the bulk processing code in Visual Basic can be reduced due to fully native language compilation in Visual C++. Besides, the image reconstruction is more efficient in Visual C++ environment because the *Windows API* functions are originated from the C++ library.

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