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IMAGING OF BUBBLY FLOW USING ULTRASOUND

Sallehuddin Ibrahim[1*], Mahdi Faramarzi[2], Mohd Amri Md Yunus[3]

[1] Department of Control and Mechatronics Engineering, Fakulti Kejuruteraan Elektrik, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
Email: salleh@fke.utm.my
[2] Sembcorp Industries Ltd.
Email: mahdi.Faramarzi@sembcorp.com
[3] Universiti Teknologi Malaysia
Email: amri@utm.my
[*] Corresponding Author

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Abstract:

Flow measurement is a vital issue in instrumentation and has been applied in the various industries. The characteristics of a single phase regime has been extensively researched. On the other hand obtaining the characteristics of a multi-component flow is more complex and traditional equipment do not provide reliable results. As such, tomography utilizing non-invasive transducers is getting attention in the industries because it does not invade the flow. Ultrasonic tomography is among the methods which is suitable for flow containing bubbles. In this project, 16 ultrasonic transducers are placed around a flow pipe. Five different phantoms representing solid flow are placed in the pipe. The flow is imaged using the linear back projection algorithm. The results show that the system was able to image the phantoms which are placed at different locations.

Keywords:

Bubbles, Flow, Imaging, Ultrasound

Introduction

Multiphase flows occur in the form of two or more thermodynamic phases in a flow pipe. Multiphase flows can be observed in various natural phenomena and in various industries. Such phases involve gas, liquid or solid and liquids or solids which cannot mix (Da Silva, 2008). Two phase flows is the most common multiphase flow where two phases which cannot mix

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but can coexist in a thermodynamic equilibrium. Bubbly flow is a form of a two phase flow which occurs at large liquid flows having a small amount of gas bubbles which are dispersed. Bubbly flow can be found in various industries such boiling water nuclear reactors, steam generators and air condition. Research on the operation and transport phenomena of bubble columns have led to better comprehension of the hydrodynamic properties, heat and mass transfer mechanisms as well as the flow regime characteristics (Sumit et al., 2022; Neha et al ,2022). Because of the strict regulations, it is urgent to develop simpler and precise instrumentations. As such tomography systems can play a significant role in industrial process (Wahab et al., 2015).

Tomography is a method for obtaining images of the internal characteristic of multiphase flow. It has been applied in multifarious industries as it can effectively obtain cross-sectional profiles of a flow and it also has the ability of distinguishing between the components of a dissimilar phase from the continuous one (Neha et al,. 2022). From these images important data of a process can be extracted which are useful in monitoring a process. From this data various parameters can be obtained such as the void fraction, flow regime and mean velocity (Hua et al., 2005). By processing signals at various positions vital data is obtained which enable investigators to get a complete picture of the region of interest.

During the last five decades there have been extensive investigation to develop tomography systems which can be applied in the industries. As such investigators came out with various tomography systems such as electrical capacitance tomography (ECT), electrical resistivity tomography (ERT), electrical impedance tomography (EIT), optical tomography (OPT), gamma-ray, X-ray, terahertz tomography, positron emission tomography and ultrasonic tomography (UT) (Wahab et al., 2014). These methods can be categorized as hard-field and soft-field. In the case of the hard field method regardless of medium, the direction of travel of the energy waves from the transmitter is constant. Ultrasonic tomography and magnetic resonance imaging are examples of hard-field tomography. Soft field is more complicated and as such it requires more computer analysis and algorithms to form the image (Wei & Soleimani, 2013). This is due to the fact that soft field is a nonlinear and on the contrary hard field is linear.

Ultrasound can detect fluctuations in acoustic impedance which is a measure of how much resistance the ultrasound beam experience as it propagates through an object (Rahiman et al., 2004). This characteristics of ultrasound enables it to be applied in liquid/gas two-phase flow having high-acoustic impedance mixtures e.g. bubbly flow (Rahiman et al., 2008). Besides, ultrasound has the advantage of being inexpensive and safe in comparison with radiation-based methods (Steiner, 2006).

Ultrasonic tomography combines hardware and software. The hardware is in the form of sensors which are placed at the exterior of a vessel. The circuits include signal conditioning, controllers and a personal computer for processing and monitoring the data. The ultrasonic sensor is excited with an electrical pulse and subsequently ultrasonic signals will be transmitted from the sensor towards the region of interest. There will be scattering and attenuation of the waves inside the pipe when they propagated through the interface of two distinctive materials. Data from all receivers and then they are transmitted to a computer which enable the images to be reconstructed. These images illustrate the distribution of the materials within the pipe.

Image reconstruction algorithms are processed by software which plays an important role in the final stage of cross-sectional monitoring of a pipe. Image reconstruction comprises two

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parts which is the forward problem and inverse problem. The forward problem is concerned with the output of each sensor and the sensing area utilizing the sensitivity maps whereas the aim of the inverse problem is to reconstruct an image to determine the profile of materials such as gas bubbles inside water.

Two main categories in the image reconstruction methods are the analytical/single step and series expansion/iterative methods (Zeng, 2001). Other techniques for image reconstruction include artificial neural network (Cierniak, 2008; Cierniak, 2009) and fusion methods (Shouxiao et al.,2011; Hengrong et al.,2023), in which tomography using two sensors is implemented. Their disadvantages is that less number of transducers are utilized that reduced accuracy However, iterative techniques can be used to reconstruct an optimal image even in the situation where the data is incomplete but they suffered mostly from low computational speed.

Ultrasonic Propagation

It is not easy to mathematically model the propagation of ultrasound and its characteristics but in bubbly flow it can be simplified to some simplified formulae. Acoustic impedance is one of the most important parameters that must be taken into consideration when considering the interaction between an ultrasound wave with a material (Z). The acoustic impedance can be mathematically expressed as:

$$Z = \rho c \tag{1}$$

in which ρ is the density of the material and c is the speed of sound. Acoustic impedance represents the resistance to the ultrasonic signals propagating in the flow pipe.

The interaction of an ultrasonic wave with two dissimilar materials will cause the wave to be reflected, transmitted or refracted. The reflection coefficient, R, and the transmission coefficients,T can be expressed as:

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right) \tag{2}$$

$$T = \left(\frac{2Z_2}{Z_2 + Z_1}\right) \tag{3}$$

where Z_1 and Z_2 are the external and internal acoustic impedance respectively. The images obtained from an ultrasonic system is obtained by tracing the reflections of ultrasonic waves and plotting the intensity of the reflected ultrasonic signals in a two-dimensional plane.

Attenuation caused the amplitude and intensity of ultrasound to be reduced as they travel. It is vital to take into account of attenuation as a decreased amplitude affect the quality of the image. Attenuation can be described by the following equation

$$I_R(z) = I_T \exp\left(-\mu z\right) \tag{4}$$

where I_R is the amplitude of the ultrasonic wave at distance z from the ultrasonic transmitter,I_T is the initial amplitude at the transmitter, z is the total path length and μ represents the coefficient of attenuation.

Ultrasonic wave inside a tomography system is slower when compared to other types of tomography systems such as electrical or optical tomography systems. This ultrasonic system has 16 transducers located around a pipe having a diameter of 110mm and the minimum data acquisition time is 8.4 ms.

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Image Reconstruction

Reconstruction of images involved detectors collecting cross section projections at different angles around the object which are then combined to produce either a two dimensional or three dimensional images. A suitable algorithm is utilized to reconstruct these images using these projections. The image reconstruction can be reformulated as an inverse problem. Radon formulated a mathematical technique which enabled an object projected to lower dimensions. The solution to this mathematical problem has been implemented for various applications such as astronomy and optics.

In the mathematical aspect, Radon transform can be expressed as the integral transform of a function over straight lines. The following equation describes a one dimensional projection of a cross section of an object $f(x,y)$:

$$p_\theta(t) = \int_{-\infty}^{\infty} f(x,y)ds \tag{5}$$

where $p_\theta(t)$represents the $f(x,y)$ projections, θ is the rotational angle, t and s represent the integral of $f(x,y)$is on the line s. In other words, the image represented by *f(x,y)* is a sequence of line integrals via *f(x,y)* at distinct offsets from the origin.

The matrix for the coordinate rotation is:

$$\begin{bmatrix} t \\ s \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \tag{6}$$

The mathematical expression for the inverse radon transform is:

$$f(x,y) = R^{-1}\{p_\theta(t)\} = {}^{1}\!/_{2\pi^2} \int_0^{\pi} \int_{-\infty}^{\infty} \frac{1}{r\cos(\theta-\varphi)-t} \frac{\partial p_\theta(t)}{\partial t} d\theta dt \tag{7}$$

where r and φ are polar coordinates and θ is the angle of rotation from 0 to π.

This represents radon inversion which is needed for all measurement data from 0 to π. Practically, to implement radon transform the number of sensors is not infinite. The level of accuracy varies with different sensor geometries and various ways of discretization.

Image reconstruction involved the forward problem and the inverse problem. The forward problem involved simulation of a sensitivity map having a discrete line from the output of the transmitter to the input of the receiver. A sensitivity map consists of a matrix having all zeros with the exception of the elements forming a part of the line from the transmitter to the receiver.

Linear back projection or simply known as LBP is the simplest reconstruction procedure which provides an estimation of the density at a point by integrating all projections. The assumption in LBP is that the projections are straight and therefore the image is smooth.

As with the case of fan-beam projection, LBP computes the density of objects in each pixel according to the following equation:

$$f(x,y) = \int_0^{2\pi} p_\theta(t) d\theta \tag{8}$$

in which $f(x,y)$ is the object, $p_\theta(t)$ is the radon space function and θ is the angles between projection and x axis.

In parallel beam geometry the equation can be modified as:

$$f(x,y) = \int_0^{\pi} p_\theta(t) d\theta \tag{9}$$

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The parallel and fan beam projections have different geometries.

The flowchart in Figure 1 illustrates the steps used for the image reconstruction algorithm.

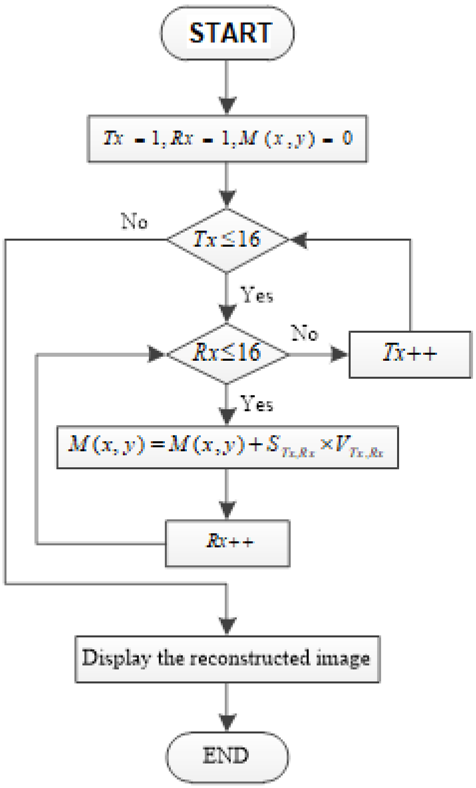

Figure 1: Flowchart showing the LBP algorithm

Figure 1 shows the program begins with the initialization of $\boldsymbol{Tx}$, $\boldsymbol{Rx}$ and $\boldsymbol{M}$ to become 1,1 and 0, respectively. As such all pixels in the $\boldsymbol{M}$ matrix are zeroed. Subsequently a projection is multiplied by the sensitivity map ($\boldsymbol{S_{Tx,Rx}}$) and the matrix which is produced is summed with the image matrix ($\boldsymbol{M}$) using the LBP. Lastly the monitor will display the image matrix.

System Configuration and Phantoms

The ultrasonic system is shown in Figure 2. The pipe is an acrylic transparent pipe which enables visual observations to be made and sixteen ultrasonic transceivers which were mounted on a circular array around the pipe. The pipe has an inner diameter of 100 mm and an outer diameter of 110mm. When the ultrasonic waves is transmitted it experience a loss of transmission power in the air. In order to create phantom, the phantoms are placed inside the PVC pipe with different diameters of 5mm, 10mm and 20mm. As part of the noise reduction strategy, coaxial cables were utilized to connect sensors to the main board. The main board includes the transmitter unit, the receiver units and the controller unit. The transmitter unit consists of a MOSFET which generates the ultrasonic burst tones. Each receiver unit consists of two amplifiers, a diode for rectifying received signals, a peak detector and sample and hold IC to keep the peak of the received signal. The controller unit was used to send control signals and collect the output of all receivers and send these data to the computer.

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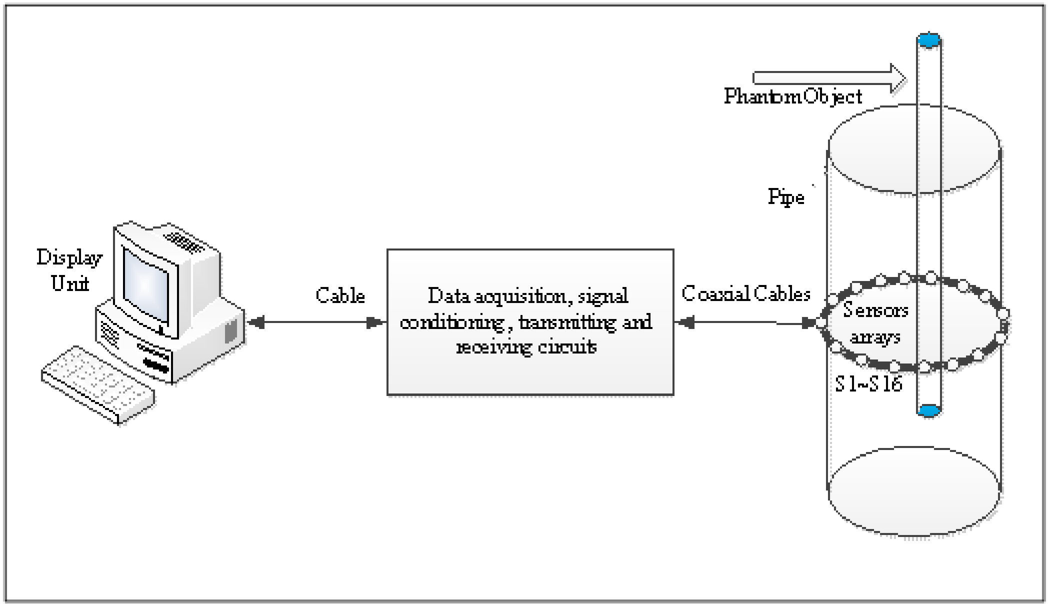

Figure 2: Ultrasonic Tomography Measurement Setup

Several phantoms representing various bubbly flow regimes were used to evaluate the performance of different reconstruction methods. Phantom 1 is a single bubble with a cross-sectional area of 48mm^2 whereas phantom 2 is a single bubble having a cross-sectional area of 192mm^2. Phantom 3 and 5 are multiple bubbles with the same size but at different locations. Phantom 4 consists of a small bubble and a larger bubble of different sizes. The results were obtained in static mode and low voidage bubbly flow was assumed.

Results and Discussion

Table 1 illustrates the results of various images reconstructed using the LBP algorithm showing different locations of phantoms placed inside a vertical pipe. Table 1 illustrates the images which are smeared by noise due to the weakness of LBP. From the reconstructed images of phantoms in Table 1, the position of the bubbles inside the pipe can be known. Phantom 1 shows a single bubble as represented by a colored circle inside the flow pipe whereas Phantom 2 shows a single bubble of a larger size also represented by a colored circle. Phantom 3 shows two bubbles at different locations represented by two circles opposite of each other. Phantom 4 shows two bubbles of different sizes but the smaller bubbles has a lower resolution that the bigger bubble. Phantom 5 shows three bubbles at different locations which are represented by three different colored circles. The system has successfully show the locations of the bubbles inside the pipe.

The LBP algorithm disseminates the data back into the image across the direction on which it was detected. That is why the images contain noises around the phantoms as well along the direction of the sensing projections. This is one of the limitations of LBP but it still manage to show the locations of all phantoms. The ability to show the locations of the phantoms means that the system can distinguish the different phases in a flow and this is important especially in the process industries.

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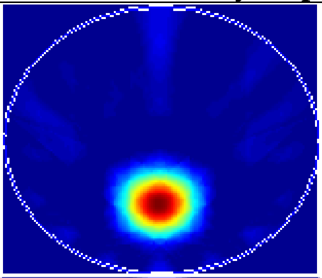
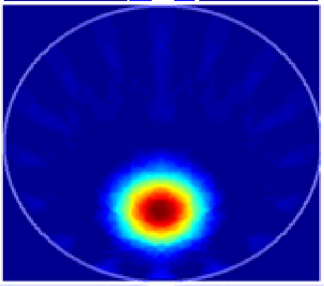
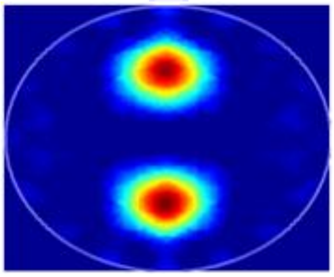
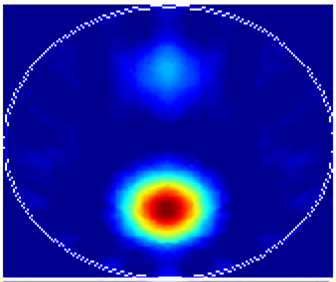
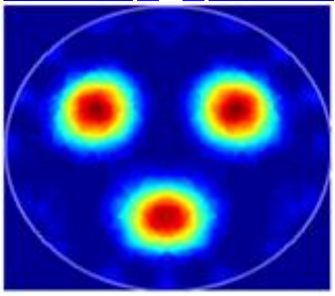
Table 1: Images of Phantoms Using the LBP Method

Phantom	Normal sensitivity map
Phantom 1	
Phantom 2	
Phantom 3	
Phantom 4	
Phantom 5	

Conclusions

Measurement of flow is extremely important in process industries and has been implemented in various industries such as the petrochemical, chemical and nuclear power generation industries. Ultrasonic tomography is among the methods which is suitable for multi-phase flow which has an acoustic impedance difference which is high. The characteristics of bubbles in a pipe was investigated in this research. In order to evaluate the effectiveness of the system,

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phantoms of different sizes are tested. Besides, the phantoms are placed at different locations and more than one phantoms are placed inside the pipe. The results show that the LBP algorithm can identify the location and dimensions of bubbles in the pipe whether it is a single bubble or multiple bubbles. This proved that the ultrasonic tomography system is a useful tool in monitoring multiphase flow.

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References

Cierniak, R.,"A 2D approach to tomographic image reconstruction using a Hopfield-type neural network," *Artificial intelligence in medicine,* 43, (2008): 113-125.

Cierniak, R., "New neural network algorithm for image reconstruction from fan-beam projections," *Neurocomputing,* 72, (2009): 3238 – 3244.

Da Silva, M. J. (2008) "Impedance sensors for fast multiphase flow measurement and imaging".

Hengrong Lan, Changchun Yang and Fei Gao “A jointed feature fusion framework for photoacoustic image reconstruction” *Photoacoustics* 29, (2023): pp 1-12.

Hua L., W. Mi, W. Ying-Xiang, M. Yi-Xin, and W. Richard, "Measurement of oil volume fraction and velocity distributions in vertical oil-in-water flows using ERT and a local probe," *Journal of Zhejiang University Science A,* 6, (2005): 1412-1415.

Neha Agarwal, Moonyong Lee, Hyunsung Kim “A Non-Invasive Method for Measuring Bubble Column Hydrodynamics Based on an Image Analysis Technique” *Processes* (2022) 10 no. 8, :1660.

Rahiman M.F., Abdul Rahim R., Wei Nyap N., and Kok San C., "Monitoring liquid/gas flow using ultrasonic tomography," *Jurnal Teknologi* 40 (2004).

Rahiman M. F., R. A. Rahim, and Z. Zakaria, "Design and modelling of ultrasonic tomography for two-component high-acoustic impedance mixture," *Sensors and Actuators A: Physical,* 147, (2008): 409 – 414.

Shouxiao Li, H. Wang, L. Zhang, and W. Fan, "Image reconstruction of electrical resistance tomography based on image fusion," in *Instrumentation and Measurement Technology Conference (I2MTC), IEEE*, (2011): 1-5.

Steiner G. and Podd F., "A non-invasive and non-intrusive ultrasonic transducer array for process tomography," *Interaction,* 99, (2006): 10-15.

Sumit R. Hazare, Chinmay S.Patil, Shivam V.Vala, Aniruddha J. Joshi, Jyeshtharaj B.Joshi, Vivek S. Vitankar, Ashwin W.Patwardhan “Predictive analysis of gas hold-up in bubble column using machine learning methods” *Chemical Engineering Research and Design* 184 (2022): 724-739.

Wahab Y. A., R. A. Rahim, M. H. F. Rahiman, H. A. Rahim, S. R. Aw and Juliza Jamaludin, "A Review of Process Tomography Application in Inspection System," *Jurnal Teknologi,* 70 (2014).

Wahab, Y. A., R. A. Rahim, M. H. F. Rahiman, S. R. Aw, F. R. M. Yunus, C. L. Goh, *et al.*, "Non-invasive Process Tomography in Chemical MIXTURES-A Review," *Sensors and Actuators B: Chemical* 210 (2015): 602 – 617.

Wei H. and M. Soleimani, "Electromagnetic Tomography for Medical and Industrial Applications: Challenges and Opportunities" *Proceedings of the IEEE,* 101, (2013): 559 – 565.

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Zeng, G., "Image reconstruction—a tutorial," *Computerized Medical Imaging and Graphics,* 25, (2001): 97 – 103.