A Study of Multiphase Flow Imaging Using Ultrasonic Tomography

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ABSTRACT

This study was conducted to investigate the multiphase flow regime in the pipelines using ultrasonic tomography technique. Multiphase flow occurs when two or more phases are flows along a closed or open pipe. The phases involved in this study are solid, liquid and gas flow which combination of these materials was tested in vertical condition. Ultrasonic tomography technique was use to solve this problem and the transmission mode was implemented. In the tomography system, number of projection will contribute to the image reconstruction result. Hence, more projection data captured tends to enhance the tomogram. In order to overcome this issue, 16 ultrasonic transceivers were used rather than separated transmitter receiver technique. This 16 transceiver will generate data equals to 32 separate transmitter-receiver sensor. It means that by using transceivers more data can be obtained because more space can be saved. Non invasive sensor arrangements applied to this system and supported with electronic measurement circuits and a data acquisition system, data for image reconstruction were generated. At the image reconstruction part, 'Linear Back Projection' (LBP) algorithm has been applied. The results obtained are useful for the monitoring of multiphase flow.

Keywords: Ultrasonic Tomography, Image reconstruction, Sensitivity map

1. Introduction

Multiphase flow is encountered in many chemical and process engineering applications. Managing systems involving two or more phases is common in areas from the processing of fuels and chemicals to the production of food, pharmaceuticals, and specialty materials. In the petroleum industry for example, the problem of multiphase flow mixtures has been of interest since the early 1980s. Since then considerable research has been conducted into the development of a multiphase flow systems suitable for use in an industrial environment [1].

The conventional approach is to separate the mixture into individual components and then measure those separately. There are some problems with the required three phase separators; their bulk, high installation cost and considerable maintenance. Therefore, it is highly attractive to have relatively simple multiphase flow systems which are capable of measuring flow of each component directly without separation[2].

Furthermore, a monitoring system that can be applied non-invasively is vital in multiphase flow system. The monitoring system should be able to provide the information about the composition of the multiphase system. Thus, tomography is the most beneficial technology that can be applied to solve the problem. Ultrasonic tomography imaging can provide images of a cross section of pipe or vessel and thus, information about the fluids inside the pipe or vessel can be extracted by analysing the image obtained.

The quality of reconstructed image depends on the number of measurement done. The higher the numbers of measurements will normally increase the spatial resolution of the system and this will enhance the quality of reconstructed image [3]. This research presents new technique in ultrasonic tomography by using ultrasonic transceiver instead of separate transmitter receiver approach. Common separate transmitter-receiver method are widely use in the ultrasonic tomography research. This method required large space in order to place around the pipeline or vessel. This is because the needs of having pair of the sensors which is transmitter and receiver. While the transceiver has an advantage of dual functioning since each transceiver have capability of become transmitter and receiver with the help of switching circuit. Therefore, the number of transceiver mounted around the measurement pipe or vessel can give up to double measurements compare to common technique.

2. Ultrasonic Tomography

The ultrasonic tomography is one of the non-invasive techniques that can be used in the industry for monitoring the flow composition, non destructive testing and extensively in medical imaging [4]. The method involves in using ultrasonic techniques is through transmitting and receiving sensors that are axially spaced along the flow stream.

An ultrasonic tomography system is based upon interaction between the incident ultrasonic waves and the object to be imaged [24]. Whenever there is an interface between one substance and another, the ultrasonic wave is strongly reflected [17] and this type of tomography technique has the advantage of imaging two components flow and gives the opportunity of providing the quantitative and real time data on chemical media within a full scale industrial process [24].

3. Recent Research on Ultrasonic Tomography in Flow Application

Since its introduction and development in the last two decades, more detailed and advance research on ultrasonic tomography in flow application have been explored and developed by many researchers worldwide.Gai *et al.* (1989) [5] has presented a paper on flow imaging using ultrasonic time-resolved transmission mode tomography. The paper considers some problems encountered in flow imaging and describe an algorithm using transmission mode ultrasound on a solid/liquid and liquid/gas flow. The algorithm takes the pulse's arrival at a specific time as its mage reconstruction data and is viewed as a modified backprojection method.

Chen *et al.* (1996) [6] from Cranfield University (UK) has presented a paper on ultrasonic tomographic technique for gas/liquid and solid particle flow measurement. An ultrasonic tomographic system and image reconstruction algorithm based on measurements of scattered waves is described.

Xu and Xu (1997) [7] from Tianjin University (China) have developed an ultrasonic facility for tomographic imaging of gas/liquid two-phase flow based on the binary logic operation and a method of "time-of-propagation along straight path". They established the principle and construction of the facility and their primary emphasize was on the evaluation of its performance in flow regime identification and cross-sectional void fraction measurement.

Warsito *et al.* (1999) [8] from Shizuoka University (Japan) has carried out a research on the cross-sectional distributions of gas and solid holdups in slurry bubble column using ultrasonic computed tomography. They utilize the transmission mode method in the experiment. The energy attenuation and the velocity changes were sense by the system in the experimental vessel due to gas and solid hold-ups and the image were reconstruct using Filtered Back Projection algorithm.

Peter Hauptman *et al.* (2002) [9] from University Magdeburg (German) have work out a paper work on the ultrasonic sensors application in the process industry in which the advantages, disadvantages, commercial example, possibilities and limitations of ultrasonic process sensors are discussed.

Since 2004, Ruzairi and M. Hafiz *et al.* had carried a research on the development of ultrasonic tomography in imaging the liquid/gas two phase flows. Transmission mode approach been implemented for sensing the flow. Till today, they have come out with many paper works on it.

Ng Wei Yap *et al.*(2005) [10] from Universiti Teknologi Malaysia has done an iimplementation of the ultrasonic tomography to determine the composition of the water and oil flow. The transmission method of ultrasonic tomography is implemented in the project as the ultrasonic waves can propagate through both the medium of water and oil. He utilizes the non-invasive methods that do not disturb the internal flow of the pipeline. The velocity of ultrasonic waves varies in water, oil and different composition of water and oil. The composition of water and oil can be determined from the measurement of this propagation time. Sixteen pairs of ultrasonic sensor mounted non-invasively around the periphery of an acrylic pipe.

Cowell *et al.* (2006) [11] from University of Leeds (UK) has review a paper on the ultrasonic signal characteristics in the presence of highly reflecting solid/liquid interfaces. The paper was split into three sections which first it review on the basic physical effects that occur when ultrasound waves pass from one material to another. Those principles were then applied and illustrated using a metal wall and surrounded by water in the second section. Last section was on the simulations to illustrate the response.

Supardan *et al.* (2007) [12] has presented a paper on the investigation of gas holdup distribution in a two phase bubble column using ultrasonic computed tomography. In the study, time averaged of gas holdup distributions were investigated in a 16cm diameter bubble column for two phase dispersed system of air-water and air-glycerol solution by implementing the transmission mode method.

Jaysuman (2009) [13] conducted a research to measure two phase liquid – gas flow regime by using a dual functionality ultrasonic transducer. Comparing to the common separated transmitter – receiver ultrasonic pairs transducer, using dual functionality ultrasonic transceiver is capable to produce same measurement results hence further improvised and contributes to the hardware design improvement and system accuracy. Due to the disadvantages and the limitations of the separated ultrasonic transmitter – receiver pair, the research presents a non-invasive of ultrasonic tomography system using ultrasonic transceiver as an alternative approach. By using 8 units of ultrasonic transceivers, the electronic measurement circuits, the data acquisition system and suitable image reconstruction algorithms, the measurement of a liquid/gas flow was realized. The system is capable of visualizing the internal characteristics of liquid and gas flow and provides the concentration profile for the corresponding liquid and gas flow.

4. Hardware Development

In process tomography system, hardware is the important part to build besides the software part. It is important as this part will acquire the data for image reconstruction. This part is fundamental to the success or failure of an acoustic imaging system. Therefore, given the object to be imaged and the specifications to be achieved, the design of front-end of an acoustic imaging system should be regarded as a first priority [5]. The hardware part is divided into two major parts which is sensing unit and the electronic circuitry to acquire the data needed for image reconstruction. Figure 1 shows the block diagram of ultrasonic tomography system.

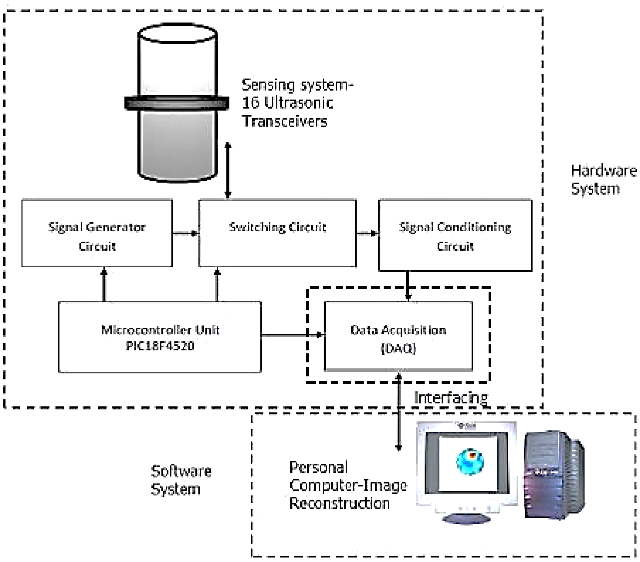


Figure 1. Ultrasonic Tomography Systems

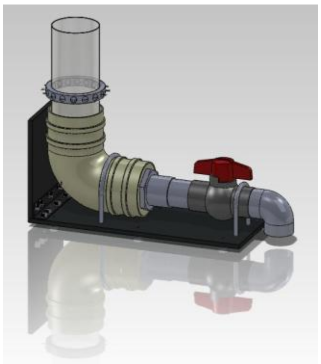
4.1 Sensing Unit

Three major parts are listed in this sensory unit which is pipe vessel, ultrasonic sensor and sensor jig. The details of the part are explained below.

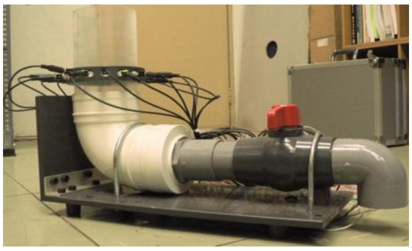
4.1.2 Pipeline / Vessel

An acrylic pipe of 110mm diameter is being used as experimental pipe in this research. It has been chosen as acrylic pipe are low cost as well as the transparency trait will let the flow inside be observe. Besides, the acoustic impedance of the acrylic pipe is almost same with the flows inside which is water, hence the penetration loss could be assumed as zero.

The pipe vessel are placed vertically since the experimental need to measure two phase and three phase flow regime including the gas hold up. The vessel has been designed using Autocad software as shown in the Figure2.



(a) Pipeline drawing

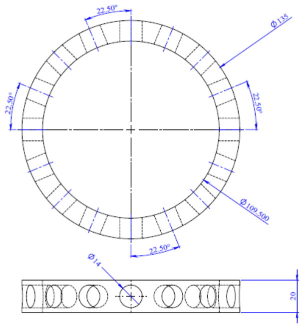


(b) Actual Pipeline

Figure 2 . Pipeline / Vessel

4.1.3 Sensor Jig

Sensor jig is used for positioning the ultrasonic transceivers at the exact location on the pipe or vessel surface. The accurate positioning of the sensors is very important since the precision of the measurement data will affect the image. A sensor jig as in Figure 3.3 was designed to put the sensor into order well around the pipe vessel. It was fabricated to fit 16 transceiver of size 14.1mm. The jig is created with accurate position, angle and thickness for each sensor. The use of sensor jig will reduce the error of the projected signal due to the echo effect (Hafiz *et al*., 2009).



(a) 2D drawing

(b) 3D drawing

Figure 3. Sensor Jig

4.1.4 Ultrasonic Transceiver

Ultrasonic transceiver is a type of transducer that converts electrical energy into high frequency sound waves and also converting sound waves back to electrical energy. It contains piezoelectric crystal materials that have the ability to transform mechanical energy into electrical energy and vice versa (Hafiz *et al*., 2010). Piezoelectric crystals have the property of changing size when a voltage is applied, thus applying an alternating current (AC) across them causes them to oscillate at very high frequencies, thus producing very high frequency sound waves.

For using piezoelectric transceiver, certain characteristics need to be evaluated to determine the properties of the transceiver that suitable for specific application. For instance, the size, frequency, sensitivity, beam angle, driving voltage and others. Selection for the right transceivers is the first priority since it is in the front-end of the ultrasonic tomography system together with associated hardware. Other factors that contribute to the selection of the sensor are the sound pressure level (SPL) and the centre frequency shift against temperature variations (Ibrahim and Salim, 2007).

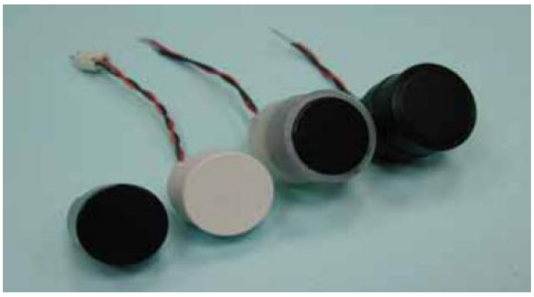


Figure 4: Ultrasonic Transceivers

The ultrasonic transceivers as shown in Figure 4 were used in this research. The transceivers are chosen because its closed face feature provides proper surface for mounting and coupling process. Besides, the capability of the transceivers for driving voltage up to 20Vrms with divergence angle 125° as well as having centre frequency of 40 kHz makes the transceivers an ideal selection for this research. Besides, the cost of each transceiver is affordable to be bought. Figure 5 and Figure 6 shows the transceivers dimenssons and beam angle.

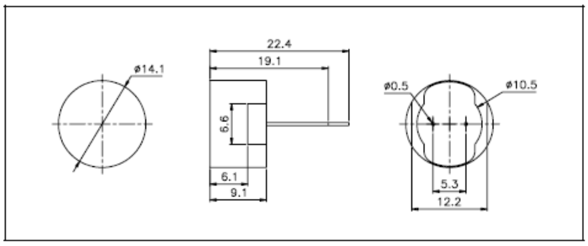


Figure 5. The transceivers dimensions (mm)

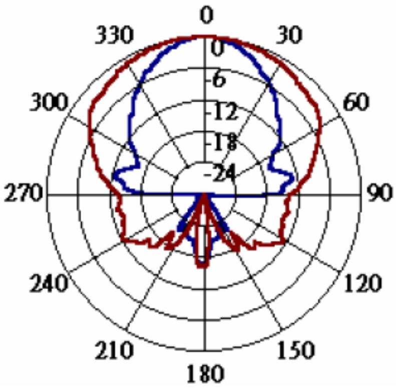


Figure 6. The Transceivers Beam Angle

This PROWAVE ultrasonic transceiver is made from aluminium and can operate up to 80°C. The robustness which is not sensitive to variation of temperature, durable and sealed construction protects against water, heat, humidity and other elements.

4.1.5 Ultrasonic Transceiver Mounting Technique

One of the significant advantages in employing ultrasonic techniques is, it enables measurements to be made without breaking into the process vessel and therefore measurements can be made where for reason of safety, hygiene, continuity of supply or cost it is not possible to break into the process vessel [25]. The invasive transducers actually contact the flow inside the pipe, for obvious reasons it is not favoured by most industries [1].

The ease of penetration depends on the acoustic impedance mismatch at each of the boundaries through which the ultrasound has to pass. Usually, a very thin air layer will exist between the face of the transducer and the surface of the pipe wall due to the microstructure of the two contacting surfaces. In ultrasonic technique, existence of air is very inefficient due to the mismatch of the sensors surface and the pipe wall [17]. Thus a couplant is needed between the sensor's surface and outer pipe. The couplant is primarily used to remove any air from the interface and match the acoustic impedances between the two different medium. Therefore it will provide the optimum transference of acoustic energy from the transmitter to the receiver.

Couplant will typically be viscous, nontoxic liquids, gels, or pastes. A number of common substances such as water, motor oil, grease, and even some commercial products like hair gel can be used as ultrasonic couplant in many applications. Table 1 show the common couplant use in ultrasonic transducer applications. For this research, the silicone glue has been chosen as the couplant. It was sandwiched between the sensor's surface and the outer pipe wall as shown in Figure 7. To maximize ultrasonic transmission, the surface should be prepared as best the application allows. It is important that the transducer faces and the pipe axis are parallel as one degree error could lead to approximately one percent change in path length [25]. Hence, the sensor jig is the solution for this problem.

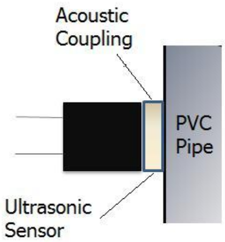


Figure 7. Ultrasonic sensor mounted on the surface of a pipe wall

Table 1. Examples of common couplant used in ultrasonic applications
(Source: http://www.npl.co.uk, 2008).

Couplant	Couplant type	Clamp required?	Viscosity	Temperature range
Silicone oil	Liquid	Yes	V Low	Low
Propylene glycol	Liquid	Yes	V Low	Medium
Glycerin	Liquid/Gel	Yes	Medium	Medium
Ultrasonic gel	Gel	Yes	Medium	Low
Brown grease	Grease	Yes	High	Low
Silicone grease	Grease	Yes	High	Medium
Petroleum jelly	Grease	Yes	High	Low
Honey	Sticky paste/gel	Yes	High	Low
Silicone compound	Elastomer adhesive	No	Elastic solid	Medium
Hot melt glue	Elastomer adhesive	No	Elastic solid	Low
Cyanoacrylate	Adhesive	No	Rigid	Low
Dental cement	Adhesive	No	Rigid	Low
Wax beads	Dry adhesive	No	V High	Low

4.2.6 Ultrasonic Sensor Arrangement

All 16 transceivers are enclosed in the jig that designed for 100mm pipe diameter. The cross section of the sensor arrangement shown in Figure 8 which is also an example of fan shaped beam sensor array. The transceivers enable the transmission and reception on the same sensor.

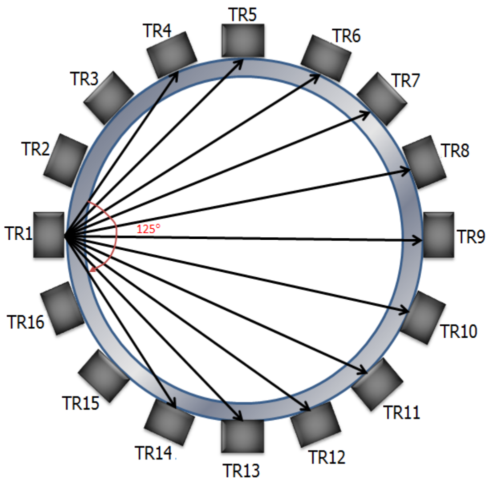


Figure 8. Ultrasonic transceivers sensor arrangement

The transceiver has 125° of beam angle and from Figure 8, it clearly shown that only 11 transceiver are within the region. The other 5 are outside the boundary including the excite one. So, there are 11 measurement in one projection, hence totally 176 measurement will be obtained. Compared to separate transmitter receiver with same beam angle on a same diameter of pipe and same sensor size only, 6 sensors within the boundary with total of 48 measurements will be taken. Therefore results in image generated that much more blurred. Figure 9 shows the ultrasonic transceiver arrangement with sensor jig.

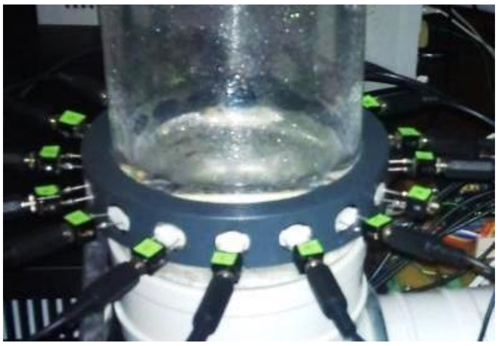


Figure 9. Ultrasonic transceiver arrangement with sensor jig

5. Electronic Measurements Circuit

Measurement circuits involved in this system are divided into five sections. The sections are:

i. Transmitter circuit/signal generator circuit
ii. Signal conditioning circuit
iii. Microcontroller unit
iv. Analog switching circuit
v. Data acquisition system

5.1 Transmitter Circuit

The transmitter circuit was designed using low noise high-performance; internally compensated operational amplifiers built using Texas Instruments complementary bipolar Excalibur process, which act as comparator. This op-amp can drive analogue signal up to +/- 44V with maximum slew rate of 45V/µs. Figure 10 shows the transmitter circuit.

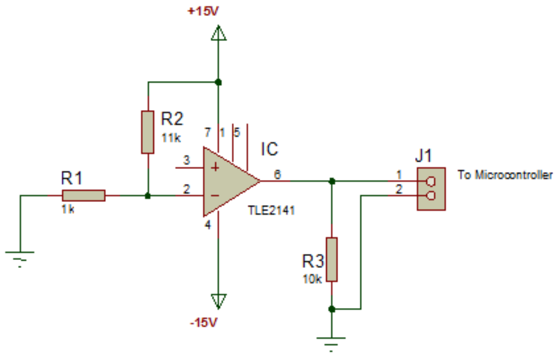


Figure 10. Signal generator circuit

The comparator was designed in such that:

$$\begin{aligned} &\text{If } V^{+} > V^{-}{}_{(ref)} \ then \ V_{out} = +Vcc \\ &\text{If } V^{+} < V^{-}{}_{(ref)} \ then \ V_{out} = -Vcc \end{aligned} \quad (1)$$

The comparator will generate 30Vp-p tone burst of 40kHz with reverberation delay of 100Hz. The duration for every pulse generation is chosen because within this delay time, the reverberation effects will stop before new excitation is activated. If the next excitation happens within this reverberation delay, overlapping echoes at the receiver will happen.

5.2 Signal Conditioning Circuit

The signal conditioning circuit consists of two components which is signal receiving circuit and peak detector circuit. The combination of this circuit is shown in Figure 11. The receiving circuit which also is an amplifier circuit using the audio operational amplifier, LM833. This op-amp is a high speed op-amp with excellent phase margin and stability. The amplifier was design in two stages with inverting amplifier connection. The first stage is the pre-amplifier with gain AA = -120 and the second stage is to amplify with gain AB = -120. The received signals are amplified through these two stages to amplify twice. The datasheet for LM833N is given in Appendix C.

A peak detector is a series connection of a diode and a capacitor outputting a DC voltage equal to the peak value of the applied AC signal. An AC voltage source applied to the peak detector, charges the capacitor to the peak of the input. The diode conducts positive half cycles charging the capacitor to the waveform peak. When the input waveform falls below the DC peak stored on the capacitor, the diode is reverse biased, blocking current flow from capacitor back to the source.

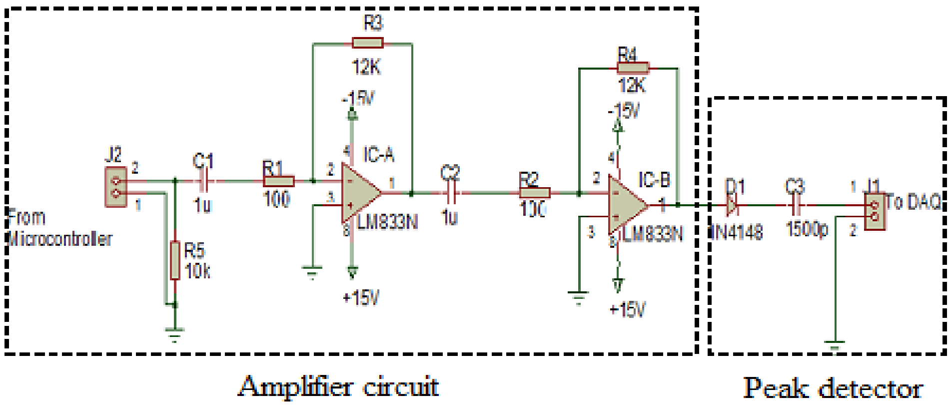
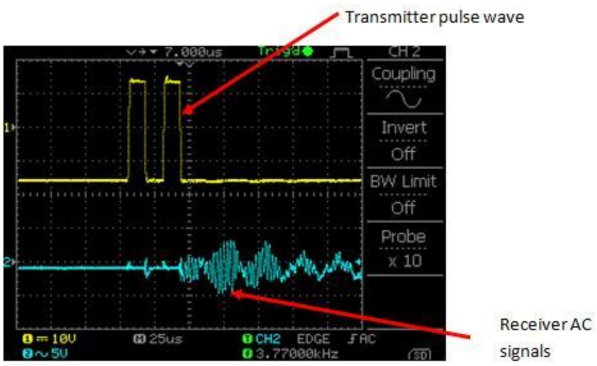
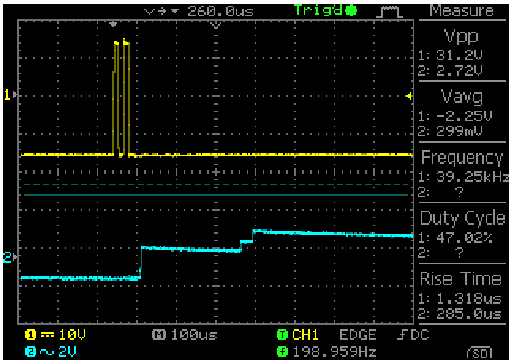


Figure 11. Signal conditioning circuit

All signals gathered from the above design are shown in Figure 12.



a) Transmitter pulse and receiver response signal



(c) Peak detector output

Figure 12. The signals captured from oscilloscope

The output signal of the peak detector will then store into the PC using data acquisition system for image reconstruction.

5.3 Microcontroller Unit

A microcontroller is a small computer on a single integrated circuit containing a processor core, memory and programmable input or output peripherals. In tomography, the microcontroller unit is function as a brain to the system. All instructions are program into the microcontroller by using a programmer. For this research, PICF4520 has been chosen. The pin configuration for of the microcontroller are illustrate in the Figure 13.

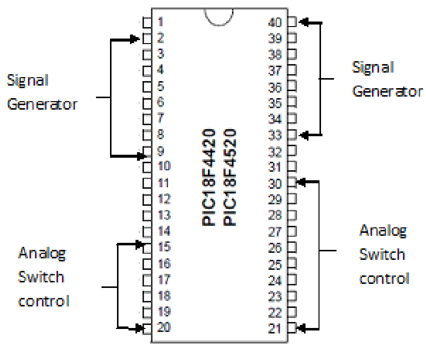


Figure 13. PIC 18F4520 pin configuration

The microcontroller will generate a dual frequency signal through pin as shown in figure above. It will generate a 40 kHz ultrasonic signal at 100 Hz as shown in Figure 14 with 50% duty cycle. 100 Hz or 10 ms duration for every pulse generation is chosen because within this delay time, the reverberation effects will stop before new excitation is activated. This is to avoid receiving overlapping echoes.

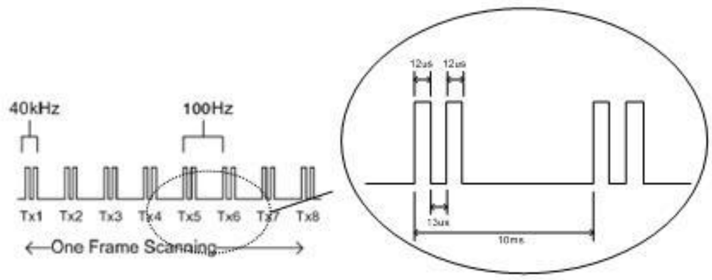
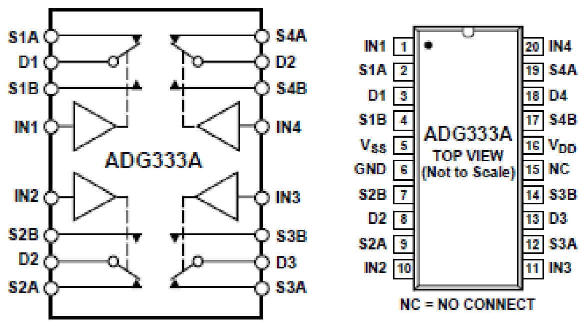


Figure 14. Pulse generation

5.4 Analog Switching Circuit

An analogue switch, also called the bilateral switch, is an electronic component that behaves in a similar way to a relay, but has no moving parts. The switching element is normally a MOSFET transistor. The control input to the switch is a standard CMOS or TTL logic input, which is shifted by internal circuitry to a suitable voltage for switching the MOSFET. The result is that logic 0 on the control input causes the MOSFET to have a high resistance, so that the switch is off, and logic 1 on the input causes the MOSFET to have a low resistance, so that the switch is on.

Analog switches are usually manufactured as integrated circuits in packages containing multiple switches typically two, four or eight. In this research quad (4 switches) SPDT analog switch ADG333A as shown in Figure 3.18 has been selected. The datasheet of this switch is given in Appendix D.



(a) **(b)**

Figure 15. ADG333A Functional block diagram and pin configuration

There are four quad SPDT switches need in the analog switch control circuit to control the 16 transceivers. A single quad SPDT switch can handle for four switches. The connection for the analog switch circuit is shown in Figure 16. This analogue switches can be control by injecting a logic "1" or logic "0" via a microcontroller into an analogue switch. The switching logic can be illustrated in below Table 2. The logic "0" on the control input causes the MOSFET to have a high resistance, thus cause the switch to OFF, and logic "1" on the input causes the MOSFET to have a low resistance cause the switch to ON.

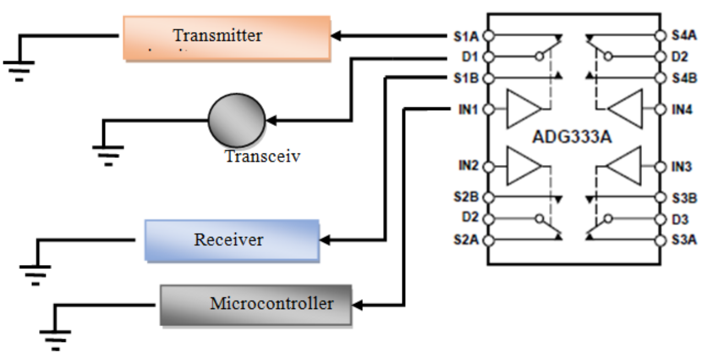


Figure 19. Analog switch connection

Table 2. Truth Table for ADG333A

Logic	Switch A	Switch B
0	OFF	ON
1	ON	OFF

6. Data Acquisition System (DAS)

In this research, Data Acquisition System from National Instruments model USB-6218 has been used (Figure 20) to acquire data from signal conditioning circuit. It can be manage via algorithm constructed in LABVIEW software.

The USB-6218 is designed specifically for mobile or space constrained applications. The plug and play installation minimizes configuration and setup time, while direct screw terminal connectivity keep cost down and simplifies signal connections. This module is bus powered from USB thus no supply power are needed.

Some advantages of this device are:

(a) 32 analog inputs at 16-bit, 250kS/s
(b) 2 analog inputs (16-bit,250kS/s)
(c) 8 digital inputs and 8 digital outputs
(d) Does not require power supply. Power up by computer using USB cable.
(e) Connects to computers via USB
(f) Device is portable and compact
(g) Supported by common software such as Visual Basic and MATLAB.

Figure 20. NI-USB6218

7. Summary

This chapter details the hardware development. The transceiver technique has been introduced in order to increase the measurement data and image reconstruction quality. In this system, sixteen 40 kHz ultrasonic transceiver has been used and the non-invasive ultrasonic tomography is implemented. As for the non-invasive technique, the acoustic coupling is needed to remove the air trapped between the transducer and the pipe wall. Thus, silicon glue has been selected as the couplant. The electronic circuit has been designed and DAS USB-6218 from National Instrument has been used for data acquisition. Figure 21 shows the whole hardware system for this project.

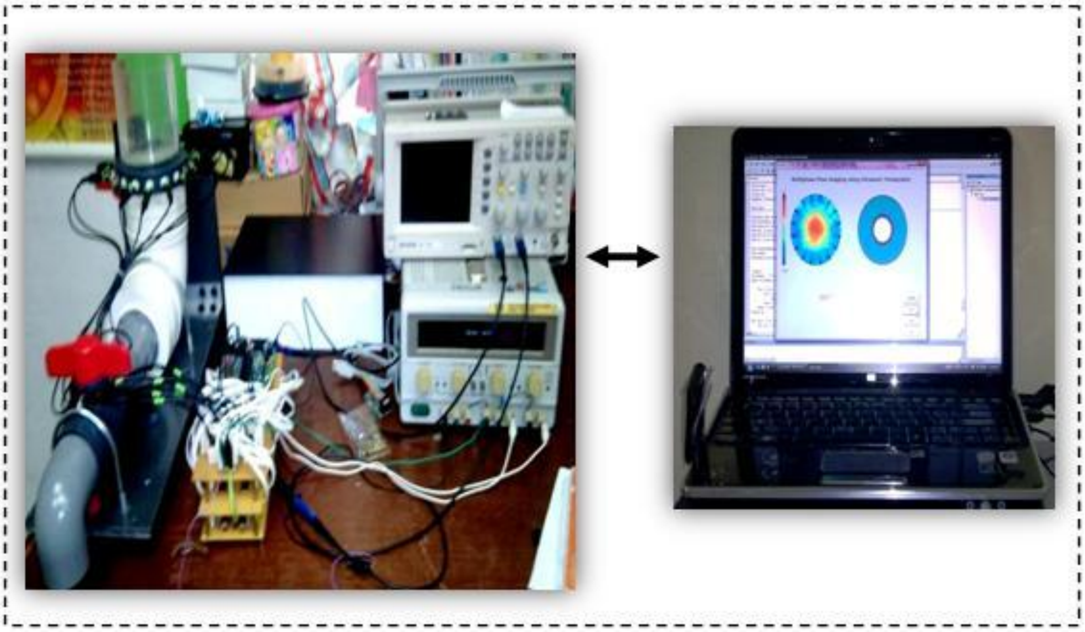


Figure 21. Ultrasonic Tomography System

8. Image Reconstruction

There are many types of image reconstruction algorithm that can be applied depends on the requirement. Some examples of image reconstruction algorithm such as Linear Back Projection algorithm (LBP), Hybrid Binary Reconstruction algorithm (HBR), Finite Element Method (FEM), and Hybrid Reconstruction Algorithm (HRA). In this research, Linear Back Projection Algorithm has been applied.

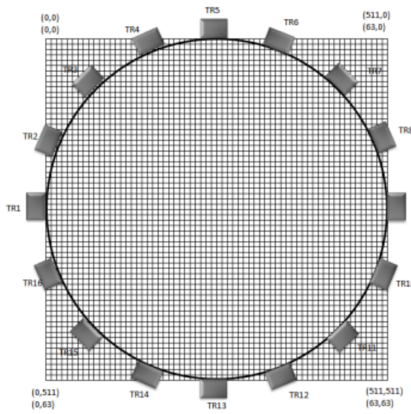


Figure 8. Image Plane Model for 64x64 Pixels Transceiver Tomogram

In order to derive this algorithm, the forward problems need to be solved first. The forward problem determines the theoretical output of each of the sensors when the sensing area is considered to be two dimensional [18] The cross section of the pipe is mapped onto 64 by 64 rectangular arrays consisting of 4096 pixels as shown in Figure 8. The forward problem can be solved by using the analytical solution of sensitivity maps which produces the sensitivity matrices [19]. Every transceiver that act as transmitters are virtually excited and every pixel on the path will be counted.

9. Experiments, Results and Analysis

The experiments were done in the pipe vessel. All the test was carry out vertically using various test material. In this section, the image reconstruction for several experimental results will be presented and discuss further.

9.1 System Calibration

In developing a measurement system, a calibration of the instrumentation is important in order to assign the standard or reference value for the system. Failure of doing calibration may bring the risk of taking false data. Decisions to be made based on such data can potentially be incorrect.

9.2 Flow Model

The calibration for this system was done in condition of full flow. During full flow, the pipe will totally fill with liquid. The liquid provide low acoustic impedance, hence the signal from transmitter could penetrate the pipe wall and travel to the receiver through the water. The value captured will be use as reference value for other experiment.

As the beam angle for each transceiver is 125°, there are only eleven transceivers within the boundary. The two transceivers beside the transmitter are outside the boundary, so total of four will not received the projected signal. These signals will be used for the image reconstruction later. Figure 9 and figure 130 shows the full flow projections and reconstructed image for full flow.

The other values captured by the other four outsiders will not be counted as they are values due to the Lamb wave. Lamb wave generated due to the complex vibration effects. The Lamb wave is a wave that propagates and travels within the pipe boundary [22]

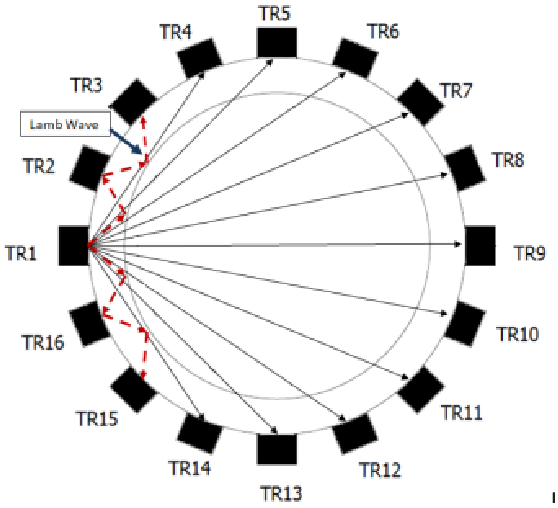


Figure 9. Full flow projections for Transceiver 1

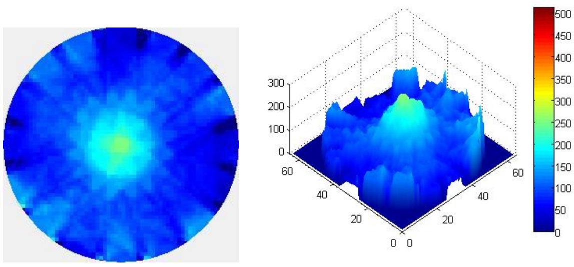


Figure 10. Reconstructed image for full flow

9.3 The Experimental Design

The experiment conducted for multiphase purpose was conducted by using several materials. Each material has different acoustic impedance value, as shown in Table 3, which is very useful for ultrasonic tomography system. The test materials and its acoustic impedance value are shown in table below. Two categories which are two phase flow and three phase flow experiment were conducted.

Table 3 : Acoustic impedance for test materials

Material	Acoustic Impedance, Z (kg/m^2s)
Water (Liquid)	$1.5x10^6$
Gas (Air)	430
Corn oil (Liquid)	1.42
Wood (Solid)	$0.15x10^6$
Cement (Solid)	$5x10^6$

The tomogram drawings were accomplished using Visual Basic 6 software. The test profile image includes together for every experiment so the comparison could be shown and discuss. The colour levels created for representing the liquid and air concentration in the tomogram is shown in Figure 11.

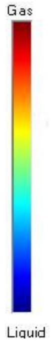


Figure 11. Colour bar representing concentration profile

In order to evaluate the image reconstructed, simulations were carried out before the experiment. The similar size and type of material was used to be placed at the respective position in the sensing area of the developed hardware system.

The difference image between the original and reconstructed images gives the quantitative and qualitative measurements that compare the quality of the reconstructed image with the original. All results presents in following section.

9.3.1 Two Phase Flow Experiment

Two phase flow means that, there are two types of components or materials inside the pipe vessel. The two phase flow systems consider were mixtures of liquids with gas, liquid mixed with solid and also liquid-liquid flow.

9.3.1.1 Annular flow

Annular flow is the situation when an empty circular tube (gas model) was put in the middle of the pipe and the gap between the tube and pipe was filled up with liquid (distilled water). In this experiment, 35mm hollow pipes were place in the middle of the vessel. This can be illustrated as Figure 12. Figure 163 shows comparison of reconstructed images between test profile and experiment for annular flow.

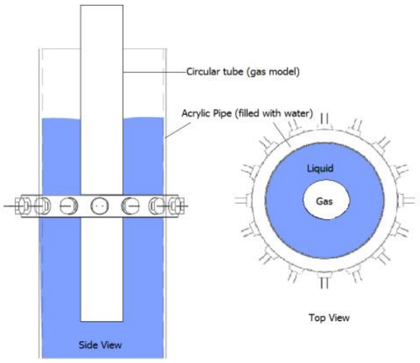
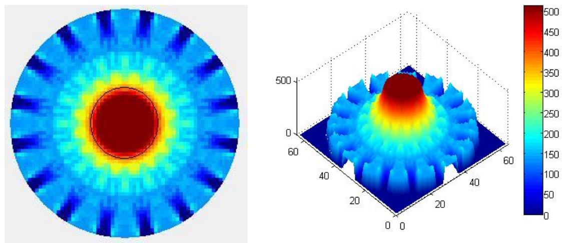
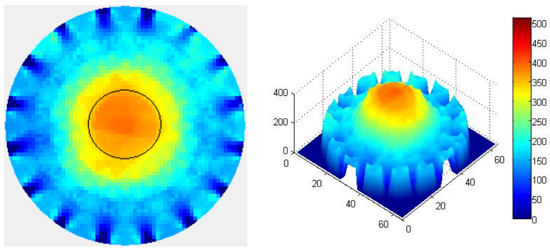


Figure 12 : Experiment vessel setup for annular flow (30mm)



(a)



(b)

Figure 13 : Comparison of reconstructed images between (a) test profile and (b) experiment for annular flow

9.3.1.2 Single Gas Hold Up

Similar as previous part, this experiment were done to investigate the two phase flow of liquid-gas. Smaller tubes of 25mm, which present gas phase, were placed inside the pipe but in a different location. Tomogram produce can be seen in Figure 14 and Figure 15.

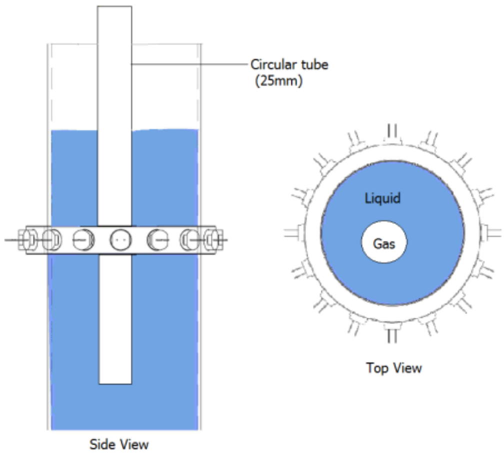
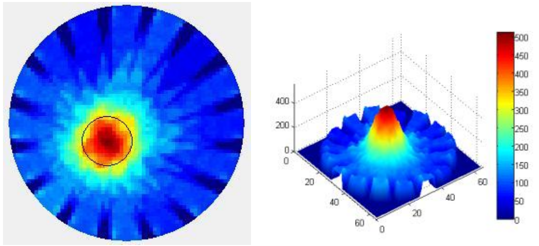
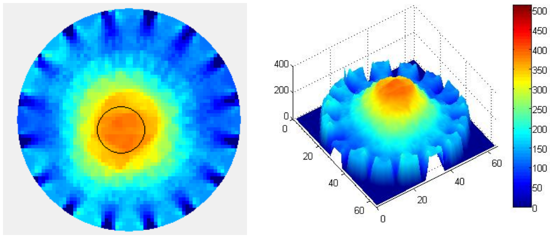


Figure 14. Experiment vessel setup for single gas hold up (25mm)



(a)



(b)

Figure 15. Comparison of reconstructed images between (a) test profile and (b) experiment single gas hold up

9.3.1.3 Dual Gas Hold Up

In this experiment, two air hold up analysis were carried out. Two circular tubes of 25 mm were inserted in the vessel. The achieve result shown in Figure 16 and Figure 17..

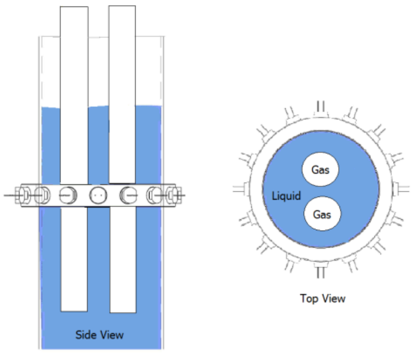
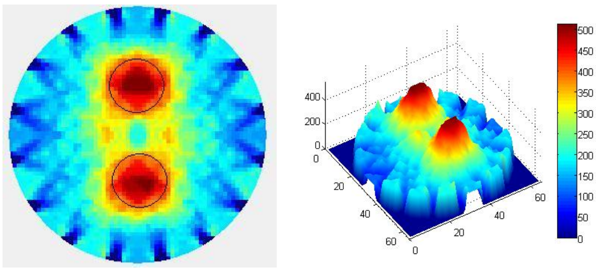
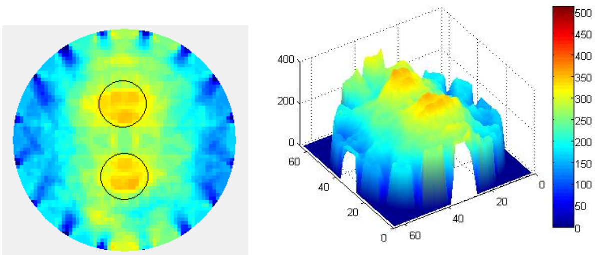


Figure 16. Experiment vessel setup for dual gas hold up (20mm)



(a)



(b)

Figure 17. Comparison of reconstructed images between (a) test profile and (b) measured system for dual gas hold up

9.3.1.4 Water and Oil

In order to investigate two phase of liquid-liquid material, corn oil was use as test material. The oils were filled in the plastic tube and place vertically inside the pipe. It can be illustrated in Figure 18. The image reconstruction is shown in Figure 19..

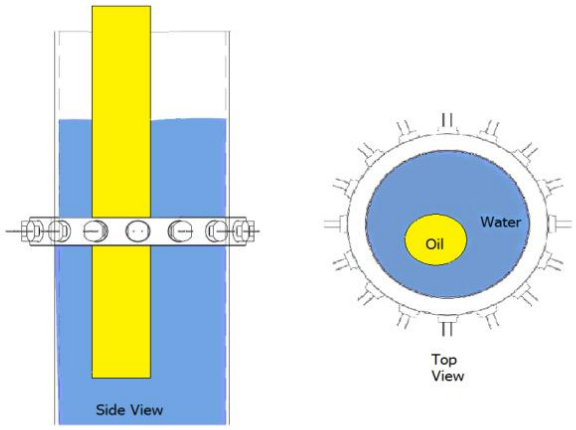
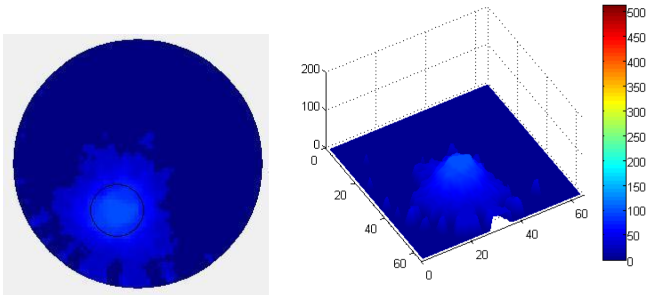
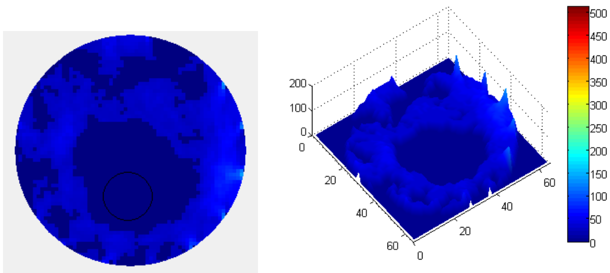


Figure 18. Experiment vessel setup for water - oil flow (25mm)



(a)



(b)

Figure 19. Comparison of reconstructed images between (a) test profile and (b) measured system for oil - water flow.

9.3.1.5 Water and Cement

Cement which has 5x10^6 kg/m^{2}s of acoustic impedance were being tested for state of liquid-solid. A 25mm of cement in cylinder tube were located as in Figure 20 and Figure 21.

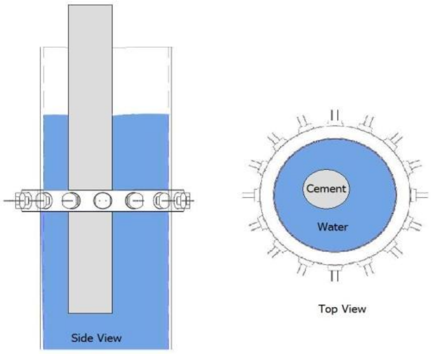
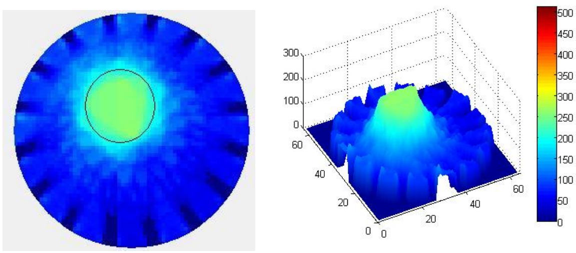
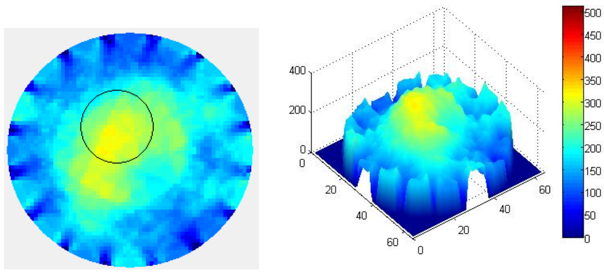


Figure 20. Experiment vessel setup for water - cement flow (35mm)



(a)



(b)

Figure 21. Comparison of reconstructed images between (a) test profile and (b) measured system for cement-water flow

9.3.1.6 Water and Wood

The other test material for solid is wood which have 0.15×10^6 kg/m^{2}s of acoustic impedance. The value of acoustic impedance of wood are less than cement, thus a comparison could be done. A wood of 28mm long and 18mm width were used. Figure 22 shows the experimental setup for water-wood flow. Figure 23 shows comparison of reconstructed images between (a) test profile and (b) measured system for wood - water

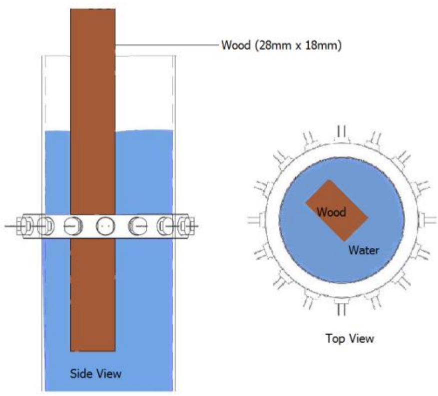
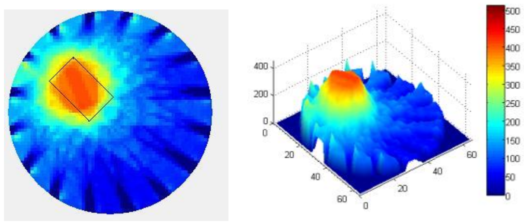
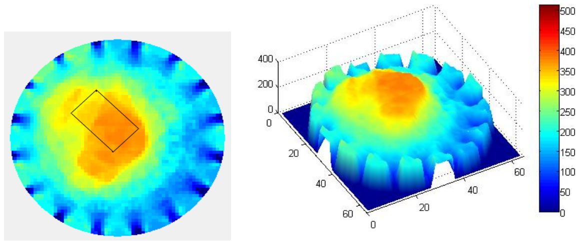


Figure 22. Experiment vessel setup for water - wood flow (28mmx18mm)



(a)



(b)

Figure 23. Comparison of reconstructed images between (a) test profile and (b) measured system for wood - water

9.3.2 Three Phase Flow Experiment

The three phase flow measurement means that there are three materials inside the vessel to be identify. This experiment conducted to identify the location and material inside the pipe. Two state of experiment were done which is liquid-liquid-gas and liquid-gas-solid. The test materials used are similar with previous testing. The experimentations are as follows:

9.3.2.1 Water, Air and Oil

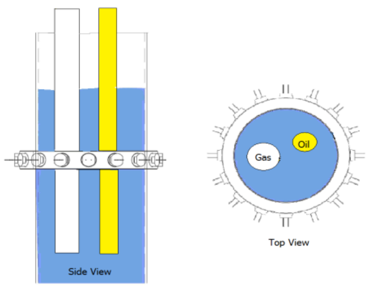
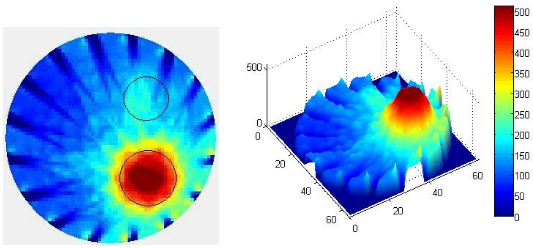
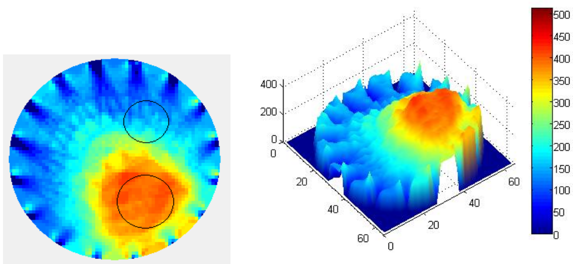


Figure 24. Experiment vessel setup for water, air (30mm) and oil flow (25mm)



(a)



(b)

Figure 25. Comparison of reconstructed images between (a) test profile and (b) measured system for oil-air-water flow

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9.3.2.2 Water, Air and Cement

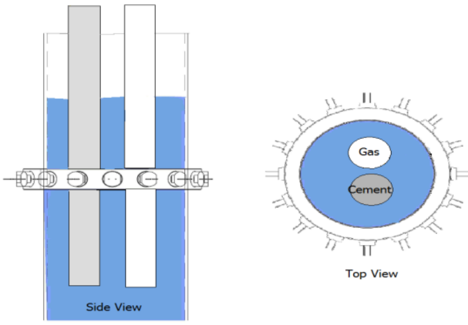
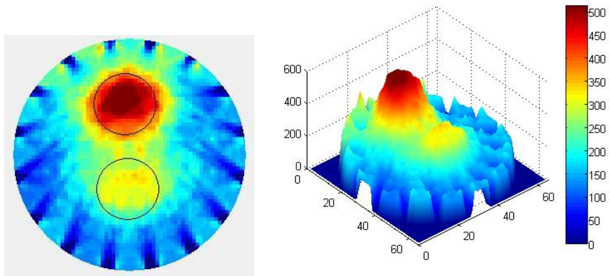
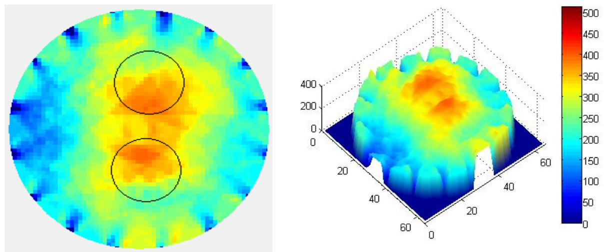


Figure 26. Experiment vessel setup for water, air (30mm) and cement flow (30mm)



(a)



(b)

Figure 27. Comparison of reconstructed images between (a) test profile and (b) measured system for cement-air-water flow

9.3.2.3 Water, Air and Wood

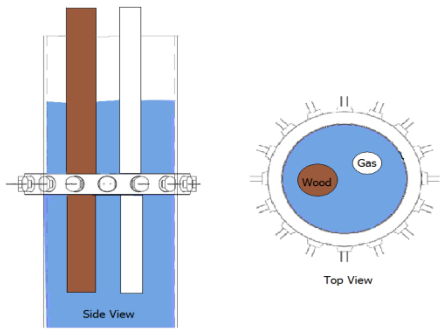
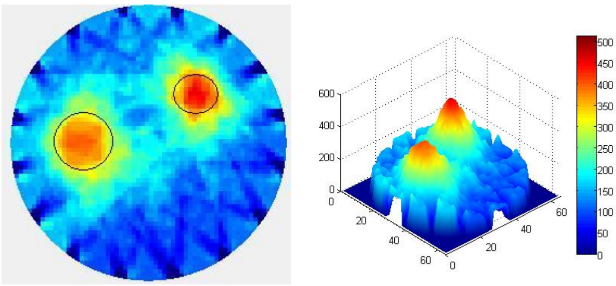


Figure 28. Experiment vessel setup for water, wood (25mm) and air flow (19mm)



(a)

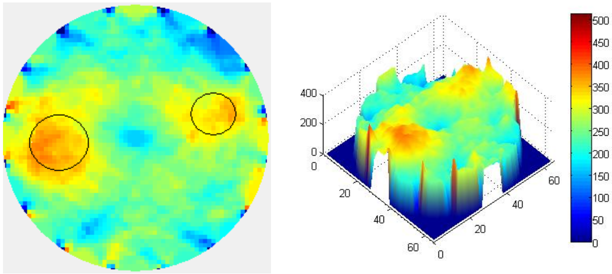


Figure 29. Comparison of reconstructed images between (a) test profile and (b) measured system for wood-air- water flow

10. Discussions

In general, for the two phase flow results, the existence of difference object in the vessel could be trace and distinguishable. This is because of the dissimilarity of acoustic impedance between the two medium. The higher the difference the more obvious it becomes.

For instance, the images of liquid-gas flow are almost the same with the test profile. It is cause by the high acoustic impedance mismatch between water and air. As explained earlier, about 99.94% of the transmit wave are reflected at the boundary of water-air hence create high value of sensor loss at the receiver.

Among the three liquid-gas images, the annular flow gives the best image in terms of size and shape. This is due to the location of the other two object are not in the middle of the pipe. It depends on the projection angle and intensity distribution at each point.

Table 2 shows the area of real, theory and experiment for the liquid-gas flow. The errors of theory and experiment area are calculated.

Table 4: Difference of area between real theory and experiment

Flow	Real (mm^2)	Theory (mm^2)	Experiment(mm^2)	Error
Annular flow	706.9	663.71	829	E_T=6.1% E_E=17.3%
Single gas flow	490.9	450.13	663.7	E_T=8.31% E_E=35.2%
Dual gas flow	314.2	303.72	330.71	E_T=3.34% E_E=5.25%

The error of the theory are because of the fault while determine the area when perform the modelling. While for the experiment error, it becomes higher because of the smeared image. The back projection technique results in blurring the object image. Nevertheless, the small error value shows that this technique could detect gas-liquid flow as well as predicting the size of the gas flow.

For water-oil flow, the densities of corn oil are almost the same with water. It clarifies the fact that only 2.73% of the waves are reflected which means this method is not suitable for imaging oil water flow.

In the case of liquid-solid flow, cement with $5x10^6$ kg/m^2s of acoustic impedance show blurry image rather than wood with $0.15x10^6$ kg/m^2s. The images successfully differentiate the two different materials although the exact shape could not be constructed.

For three phase flow results, it shows that this technique could detect the location of object other than liquid phase. However, it could not differentiate the type of the object itself. In water-oil-air flow, only the gas phase clearly appeared while corn oil is not stand out. As discussed earlier, the percentage of transmit wave are high so the sensor loss are low thus did not give much differences of the density.

As shown above, the presence of air-cement and air-wood could be detected. Nevertheless the intensity of those two objects is almost same, but still the size is dissimilar. It is due to the transmit wave are cross each other hence effect the sensor loss value received by opposite receiver.

Obviously, all the reconstructed images turn out to blur the object. This is due to the process of back projection. The back projected data values that smeared back across the unknown density function and overlapped to each other lead to the formation of smearing effect.

Another reason that causes dissimilarity of the experiment image and modeling image are the sensitivity of the transceiver itself. The fault of sensor fabrication affects also the quality of the image. Not all of the sensor could transmit or receive with corresponding value.

Besides that, the number of projection will also affect the image quality as LBP algorithm depends on projection number to increase the intensity of the object.

11. Analysis of Transceiver Performance

The performance of test profile for eight transceivers and sixteen transceivers are evaluated. The results are as follows.

i. Two Phase Flow

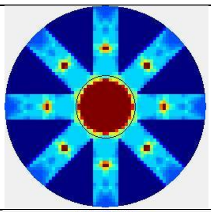
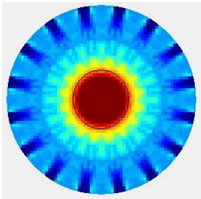
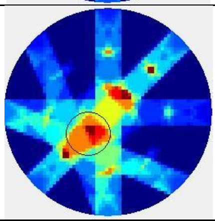
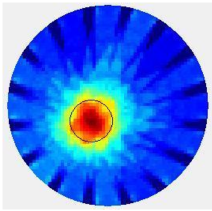
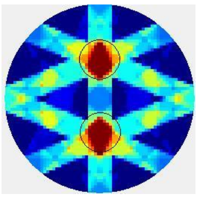
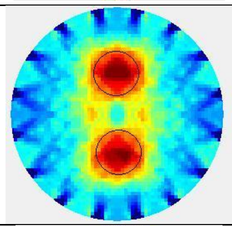
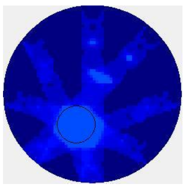
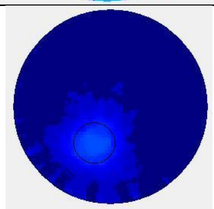
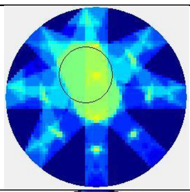
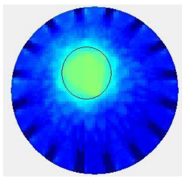
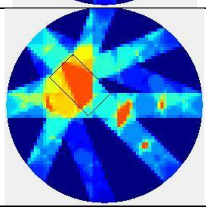
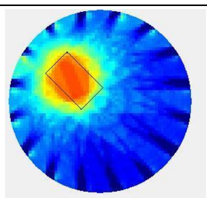
8 TRANSCEIVERS	16 TRANSCEIVERS	FLOWS
		Annular flow
		Single gas hold up
		Dual gas hold up
		Water and Oil
		Water and Cement
		Water and Wood

Figure 3. Image comparison in two phase flow for eight and sixteen transceiver.

ii. Three phase Flow

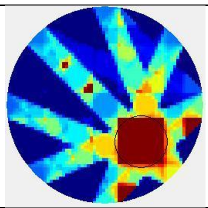
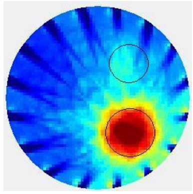
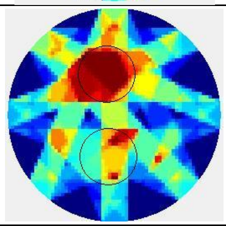
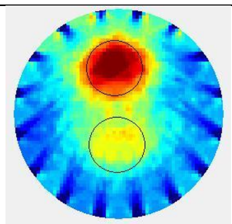
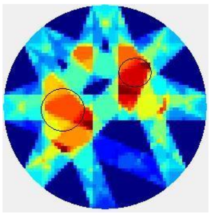
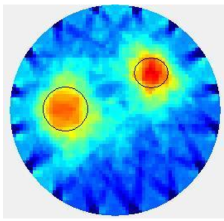
8 TRANSCEIVERS	16 TRANSCEIVERS	FLOWS
		Water, Air and Oil
		Water, Air and Cement
		Water, Air and Wood

Figure 31. Image comparison in two phase flow for eight and sixteen transceiver.

Based on results image, it's verified that higher number of projections could enhance the image quality. Beside, the results for three phase flow are even worse as it cannot detect the object correctly. Again, the messy effect is due to back projected data value that smeared back across the image.

This explained the advantages of using transceiver rather than separate transmitter receiver. The dual functionality ultrasonic transceiver has the potential and advantages of increase the amount of sensors while remain the pipe size. Thus, the coverage are of the pipe could be increase. Hence, the reconstructed image will greatly enha

12. Summary

Thissectionr presents the results from the experiments carried out for multiphase flow. The multiphase flow classified as two phase which is gas-liquid, liquid-liquid and solid-liquid, and three phase which is gas-solid-liquid flow. The materials used are water, corn oil, air, cement and wood which water as the reference for every experiment. Linear back projection (LBP) algorithm used for image reconstruction.

The results show that the ultrasonic tomography system is successfully implemented for imaging multiphase flow. The used of transceiver is proven that it gives advantages in enhance the quality of image by increasing the number of projection compared to separate transmitter receiver method.

Nevertheless, the images are hardly define the types of object through the reconstructed image for three phase flow, but could detect the location of the object successfully.

The systems with eight transceiver are almost cannot detect the three phase flow model as the number of projection and the coverage area are limited. Hence, the use of these transceiver gives advantages as it could double up the number of transceiver while keep the size of pipe.

13. Conclusions

A non-invasive of multiphase flow imaging using transceiver method has been developed and implemented successfully. Sixteen transceivers have been successfully implemented non-invasively in this research. The fabrication including designing the sensor jig and mounting using suitable coupling mater. The software for image reconstruction has successfully created using Visual Basic 6.0 software. The algorithm for sensitivity map has also created in this software. The program could also display the image through GUI and store the concentration profile value in the matrix form

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