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ON MONITORING OF LIQUID/GAS FLOW USING ULTRASONIC TOMOGRAPHY

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Abstract. In this paper, 16-pairs of ultrasonic sensors have been used. The system is capable of visualising the internal characteristics of liquid and gas flow, and provides the concentration map of the corresponding liquid and gas flow. The investigations were based on the transmission and reception of ultrasonic sensors that were mounted circularly on the surface of test pipe. Three experiments were carried out on the test pipe to simulate the horizontal flow of liquid (water) and gas (air) with three static conditions. The results showed that as the distance between the transmitting sensor and receiving sensor increases, the ultrasound will consume a longer travel time to reach to the target.

Keywords: Ultrasonic, ultrasonic tomography, liquid and gas flow, flow measurement system

1.0 INTRODUCTION

Ultrasonic sensors have a long history of success in a variety of non-tomographic applications: in process measurement, non-destructive testing, and single viewpoint medical imaging [1–3]. In general, the object or field will interact with an ultrasound beam through some form of acoustic scattering. The interaction may then be sensed to yield information about the object or field. This is viable only when a significant interaction occurs, which is related closely to modulus of elasticity and density variations, for example, in liquid containing gas bubbles.

Ultrasonic sensor is sensitive to the density of sound changes and has the potential for imaging component flows such as oil/gas/water mixtures that frequently occur in the oil industry. Plaskowski *et al.*, [2] pointed out the ultrasonic techniques that could be used to image the gas component (large density differences), while capacitance techniques could be used to image the water component (large permittivity difference); thus providing individual images of the gas and water components flowing in an oil well, riser, or pipeline.

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2.0 ULTRASONIC TOMOGRAPHY

The imaging and measurement of flows provide an important inspection method in industrial processes. Ultrasonic tomography allows the reconstruction of images which enables the measurement of certain characteristics of objects that cannot be easily obtained by other methods. Ultrasound is able to detect changes in acoustic impedance (Z), which is closely related to the density (ρ) of the media ($Z = \rho c$, where c is the velocity of sound), and thus complements other tomographic imaging technologies such as Electrical Capacitance Tomography (ECT), and Electrical Impedance Tomography (EIT) [4]. Ultrasonic tomography has mainly been researched with a reduced number of transducers (commonly two) which are rotated around the objects of interest [3]. These systems cannot produce the rapid data capture that would lead to real-time imaging and measurement of a highly fluctuating target area.

Wherever there is an interface between one substance and another, the ultrasonic wave is strongly reflected. However, it is difficult to collimate and problems occur due to reflections within enclosed spaces, such as metal pipes [5]. There are two types of ultrasonic signals that are usually used. They are the continuous signal and the pulsed signal [3]. Using a continuous signal will provide continuous impact on the crystal, whereas by using pulses, the interval of the transmission and reception signal can be estimated. Using the ultrasonic method in air is very inefficient due to the mismatch of the sensors' impedance as compared with air's acoustic impedance. New types of sensor are continually being developed but the effective ones are expensive. The design of this sensor is critical to reduce any sensor's ringing [3].

The sensor system can be classified into transmission mode, reflection mode, and emission mode techniques [6]. The transmission mode technique is based on the measurement of the changes in the properties of the transmitted acoustic wave, which are influenced by the material of the medium in the measuring volume. The change of the physical properties can be the intensity, polarization, and/or transmission time (time-of-flight). The reflection mode technique is based on the measurement of the position and the changes of the physical properties of wave or a particle reflected on an interface. Similar to the reflection mode technique, there are some techniques based on diffraction or refraction of wave at a discrete or continuous interface in the object space. The emission mode technique is based on the measurement of the intensity and the spatial orientation of the radiation, emitted from the inside of the measurement plane.

Ultrasonic technique also has potential for multi-modal sensing as the technique could be based on the measurement of the energy attenuation, and the transmission time (velocity). Examples of ultrasonic techniques for differentiating three-phase components in gas-liquid-solid system are the use of ultrasonic signal analysis method [7-9], multi-frequency ultrasonic technique [10], and a single-modal ultrasonic technique with two-parameter sensing (the energy attenuation and the transmission time) in the object space [11].

3.0 CONSIDERATION IN IMPLIMENTING ULTRASONIC TRANSMISSION-MODE TECHNIQUE

The ultrasonic tomography poses a problem where the real-time performance is paramount: the complex sound field sensed by transducers often results in overlapped, or multiple reflected pulses, which introduce errors and the inherent slow propagation speed of ultrasound lowers the scanning speed. To eliminate these problems, Li and Hoyle [12] presented a spectral analysis strategy, which examined the phase information of reflected ultrasonic signal detected by a transducer. A circular detector array was used to enable the real-time data acquisition. Warsito *et al*. [13] had mentioned some considerations in implementing the transmission mode ultrasonic technique to gas-liquid-solid systems. There are two major constraints on the application of the transmission mode ultrasonic technique:

- Limitation by attenuative media.
  As a gas-liquid (the reflection rate almost 100%) or a liquid-solid interface (the reflection rate about 90%) is almost a perfect mirror for acoustic wave, the present system can only be used in case of sparse bubbly or particulate systems. When the number of bubbles and/or the particles over the cross-section are too large, and the projection area of the bubbles and / or the particles on the cross-section of the transducer becomes larger than the axial aperture, there will be not enough space for the acoustic beam to pass through and arrive at the corresponding receiver along a straight path. Therefore, total holdups (gas and solid) of up to 20% may be a reliable limit for the application of the measuring technique. Attenuation caused by a viscous liquid or a long transmission path may be overcome by the use of a more powerful ultrasonic generator or amplifier.

- Limitation by complex sound field.
  The complex sound field sensed by transducers could result in overlapped or multiple reflected pulses, which introduce errors in the measurement. To avoid this, the most common approach is to use only the first time-of-transmission signal corresponding to a straight path, as the reflected signal will be detected after the first time-of-transmission signal. The use of high frequency and a planar signal by allowing a free-bubble region between the transducer and the measuring volume (coupling) will also decrease the multiple scattering.

3.1 Modes of Ultrasonic Wave Propagation

In solids, ultrasonic waves can propagate in four principle modes that are based on the way the particles oscillate. Ultrasonic can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. In liquid and gas medium, an ultrasonic beam advances as a longitudinal wavefront, in common with all sound waves. However, at surfaces and interfaces, various types of elliptical or complex vibrations of the particles make other waves possible. Some of these wave modes are the Rayleigh and Lamb waves. Lamb waves are complex vibrational waves that travel through the entire thickness of a material. Propagation of Lamb waves depends on the density, elasticity, and material properties of a component, and they are influenced by the selected frequency and material thickness [3].

4.0 ULTRASONIC SENSOR SET UP

Since using the ultrasonic method in air is very inefficient due to the mismatch of the sensor impedance compared to air acoustic impedance, an acoustic coupling is introduced between the sensor surface and the outer pipe wall. The acoustic coupling is needed to match the acoustic impedances between two different mediums and it will provide the optimum transference of the acoustic energy from the transmitter to the receiver. Moreover, the coupling will also provide a free-air region between the sensor surface and the pipe wall. This is because, in the air, the acoustic energy will be scattered and thus, none of the transmitted signal could emit through the pipe. Glycerin is a very fine grease and therefore, is chosen to be the coupling. It is sandwiched between the sensor surface and the outer pipe wall.

Ultrasonic sensors will be evaluated by circularly arrayed 16-pairs non-invasively on the surface of the process vessel. Using the transmission mode method and the fan-beam projection technique, the ultrasonic transmitter will transmit pulses at 40 kHz through the process vessel to the point of interest.

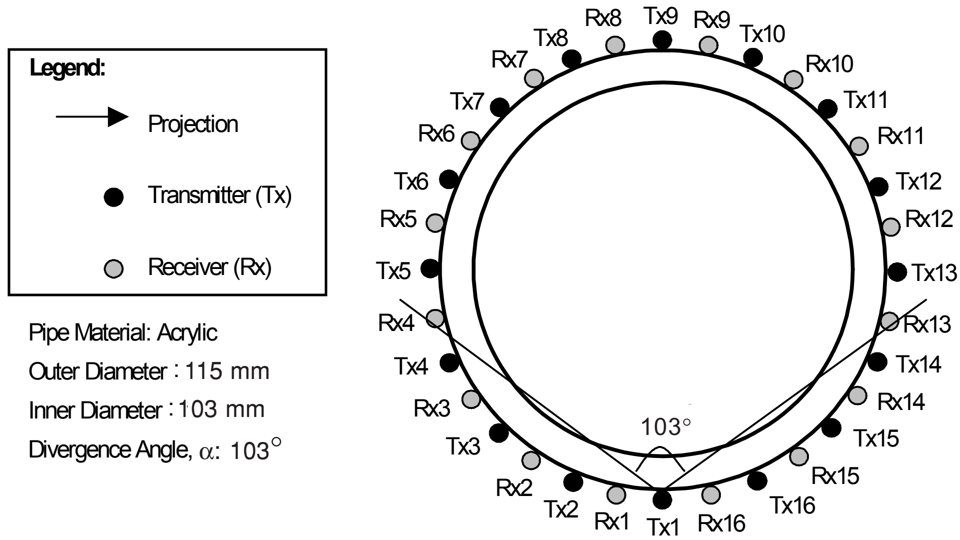

Figure 1 The sensor fixture configuration

The sensor fixture configuration is as shown in Figure 1. The T×1, T×2, T×3, etc., represent the transmitters whereas the R×1, R×2, R×3, etc., represent the receivers. With 103° divergence angle, each projection from the transmitting sensor will only cover for 10-channels of receiving sensors. The arrangement of the ultrasonic sensors around the process vessel is shown in Figure 2.

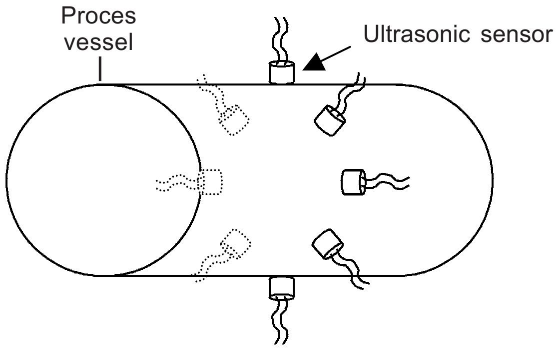

Figure 2 The arrangement of the ultrasonic sensors around the process vessel

5.0 ELECTRONIC MEASUREMENT TECHNIQUE

The basic hardware preparations are the signal generator, signal conditioning circuit, and the data acquisition system or an interfacing peripheral. The electronic measurement system is shown as below:

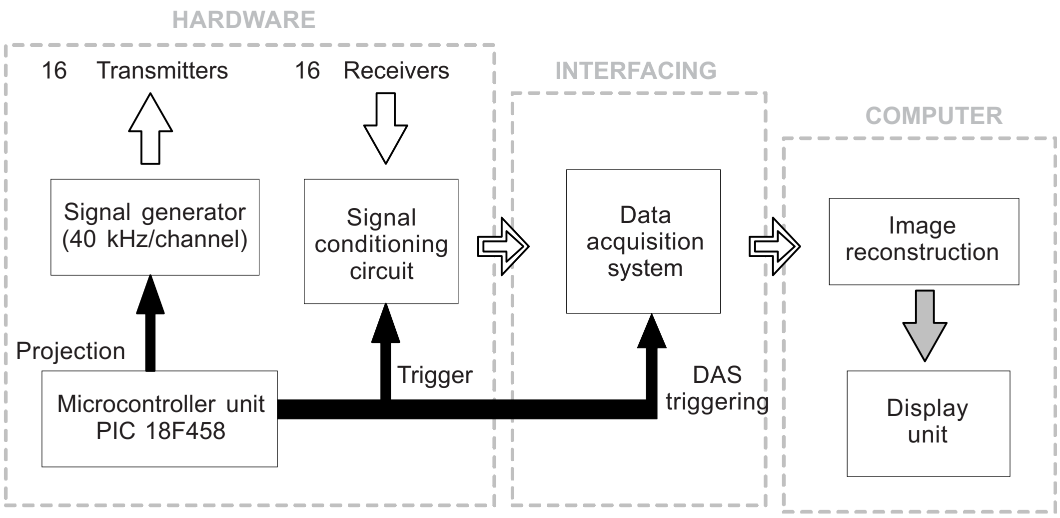

Figure 3 Block diagram of the Ultrasonic Tomography System

A PIC18F458 microcontroller is used to control the projection of 40 kHz pulses to the ultrasonic transmitters. The received signals are then being amplified to an appropriate voltage level. A received signal which has been directly transmitted can therefore be distinguished from a reflected signal, which must have a longer delay time. If a directly transmitted signal is detected, it can be concluded that there is no obstacle between the transmitting and receiving sensors [2].

The receiver signal is however, determined by the first time-of-receiving signal's amplitude in a straight path from the corresponding transmitter, and the reflected signal will be detected after the first time-of-receiving signal [13]. An example of the received ultrasonic waveform is shown in Figure 4.

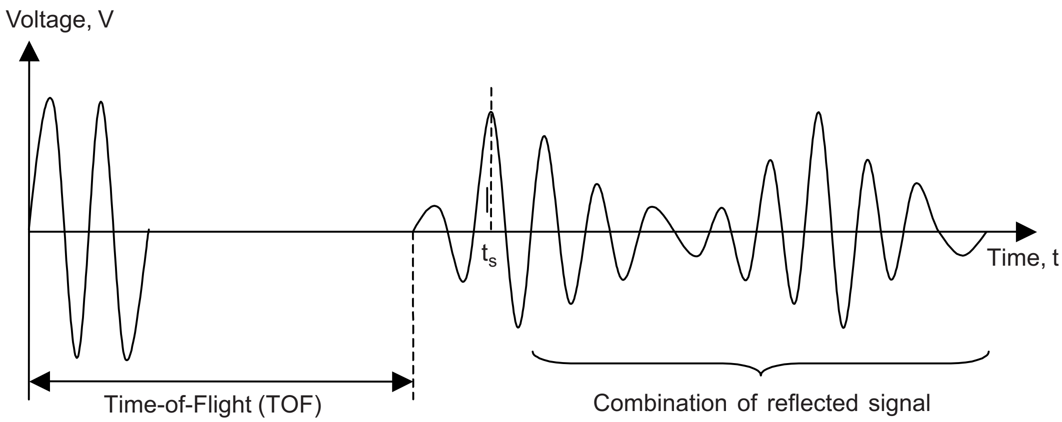

Figure 4 The received Ultrasonic Waveform and the Time-of-Flight

A sample and hold technique is used to capture (sample) and hold the analog voltage in a specific point in time (t_s) under control of an external circuit (microcontroller). By using the data acquisition system, the sampled signals are acquired into the PC. At the same time, a suitable image reconstruction algorithm such as the back-projection algorithm can be used for visualizing the internal characteristics of the corresponding process vessel.

6.0 EXPERIMENTS, RESULTS AND ANALYSIS

The investigations were based on the transmission and reception of ultrasonic sensors that were mounted circularly on the surface of test pipe (acrylic pipe). Three experiments were carried out on the test pipe to simulate the horizontal flow of liquid (water) and gas (air) with three static conditions that are:

(i) The full flow condition (100% filled with water).
(ii) The half flow condition (stratified flow, 50% filled with water).
(iii) The zero flow condition (not filled with water).

For the experimental purpose, the flow for three conditions mentioned above are assumed static, and the flow conditions are represented by the test pipe, whereby it is filled and not filled with water. These assumptions are to ease the experiment and analysis for the liquid and gas two-phase flow.

The liquid and gas are both inhomogeneous medium and therefore, they have a large difference in the acoustic impedance. The acoustic impedance for liquid such as water is low, about 1.5 Mrayl, whereas the gases have quite high acoustic impedance of about 4.3×10^{-4} MRayl. The ultrasonic beam by the longitudinal waves could penetrate through the pipe from the transmitting sensor to the receiving sensor within a low acoustic impedance media such as liquid (as shown in Figure 5). Any obstacle structured by the gases could block and reflect the transmitted signals from being sensed by the receiving sensors, due to the high acoustic impedance in the gases. For a stratified flow, the gas phase flows in the upper section and the liquid in the lower section. As a result, some of the receiving sensors will receive the transmitted signals and some will not due to the reflection at the liquid boundary (as shown in Figure 6). For a zero flow, the gas phase will occupy the whole section, thus none of the receiving sensors can receive the transmitted signals. Since the acoustic impedance is very high in the gas section, the Lamb Waves will occur and travel within the pipe boundary (as shown in Figure 7).

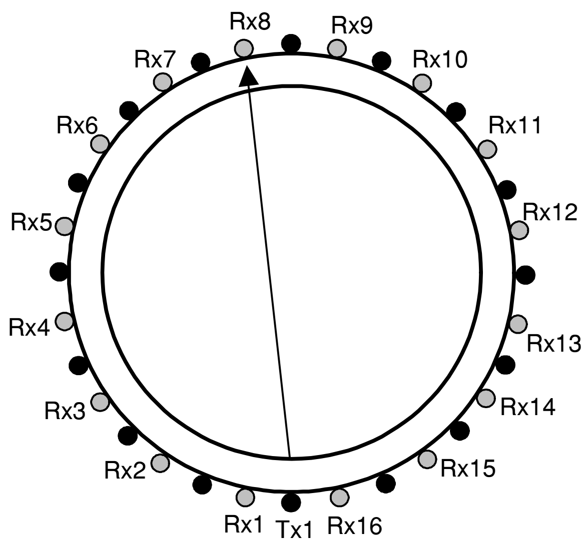

Figure 5 Ultrasonic beam penetration by the longitudinal waves from T×1 to R×8

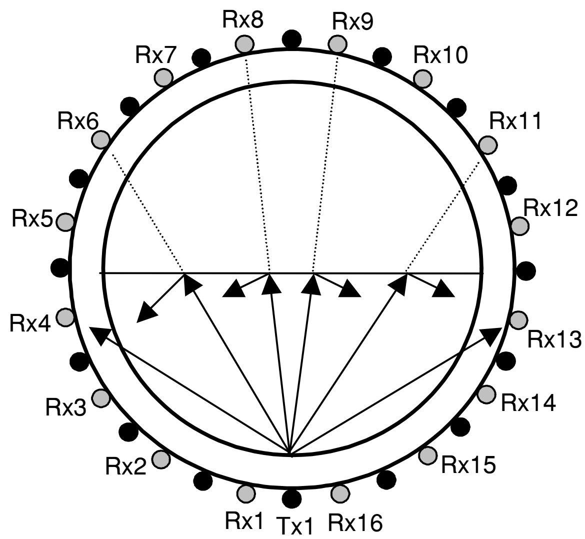

Figure 6 Transmitted and reflected ultrasonic beam from T×1

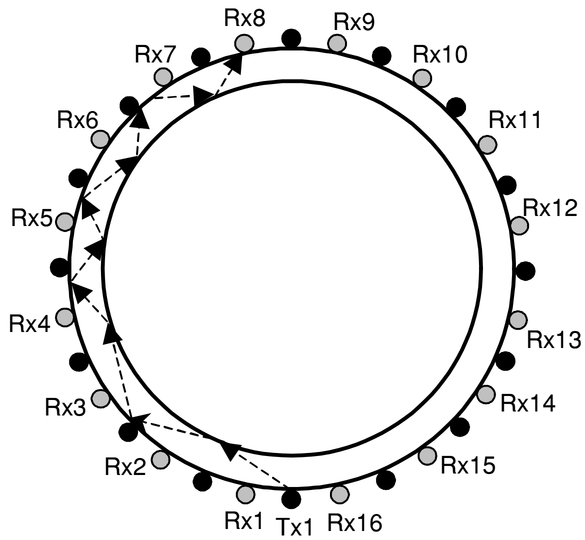

Figure 7 Ultrasonic beam with Lamb Waves propagation from T×1 to R×8

As shown in Figures 5 and 7, the distance of ultrasonic penetration by the longitudinal waves from T×1 to R×8 is shorter, compared to the Lamb Waves propagation from T×1 to R×8. As the distance between the transmitting sensor and the receiving sensor increases, the ultrasound will consume a longer travel time to reach to the point of interest. This travel time may then be assumed to be proportional to the distance that they had traveled [14]. By using TDS 3014 Digital Oscilloscope, the time-of-flight for every receiving sensors are determined. Results for the complete cycle of projection T×1, T×4, and T×12 are tabulated in the Table below.

Table 1 The Time-of-Flight for the flow simulation of Projection T×1

Projection	Full flow	Half flow	Zero flow
T×1 – Rx4	54.4 μs	54.4 μs	59.2 μs
T×1 – Rx5	68.8 μs	74.0 μs	74.0 μs
T×1 – Rx6	74.4 μs	94.4 μs	94.4 μs
T×1 – Rx7	81.2 μs	118.0 μs	118.0 μs
T×1 – Rx8	84.4 μs	128.0 μs	128.0 μs
T×1 – Rx9	84.8 μs	128.4 μs	128.4 μs
T×1 – Rx10	81.0 μs	117.8 μs	117.8 μs
T×1 – Rx11	74.4 μs	94.4 μs	94.4 μs
T×1 – Rx12	68.6 μs	73.8 μs	73.8 μs
T×1 – Rx13	54.2 μs	54.2 μs	59.0 μs

Table 2 The Time-of-Flight for the flow simulation of Projection T×4

Projection	Full flow	Half flow	Zero flow
T×4 – Rx7	54.6 μs	59.2 μs	59.2 μs
T×4 – Rx8	68.6 μs	74.2 μs	74.2 μs
T×4 – Rx9	74.2 μs	94.6 μs	94.6 μs
T×4 – Rx10	81.4 μs	118.2 μs	118.2 μs
T×4 – Rx11	84.4 μs	128.2 μs	128.2 μs
T×4 – Rx12	84.2 μs	128.0 μs	128.0 μs
T×4 – Rx13	81.2 μs	81.2 μs	118.0 μs
T×4 – Rx14	74.2 μs	74.2 μs	94.6 μs
T×4 – Rx15	68.6 μs	68.6 μs	74.2 μs
T×4 – Rx16	54.0 μs	54.0 μs	58.6 μs

Table 3 The Time-of-Flight for the flow simulation of Projection T×12

Projection	Full flow	Half flow	Zero flow
T×12 – Rx15	54.0 μs	59.4 μs	59.4 μs
T×12 – Rx16	68.6 μs	74.0 μs	74.0 μs
T×12 – Rx1	74.4 μs	94.0 μs	94.0 μs
T×12 – Rx2	81.4 μs	118.4 μs	118.4 μs
T×12 – Rx3	84.2 μs	128.6 μs	128.6 μs
T×12 – Rx4	84.6 μs	128.2 μs	128.2 μs
T×12 – Rx5	81.2 μs	118.0 μs	118.0 μs
T×12 – Rx6	74.6 μs	94.2 μs	94.2 μs
T×12 – Rx7	68.4 μs	73.8 μs	73.8 μs
T×12 – Rx8	54.2 μs	59.4 μs	59.4 μs

The data from Tables 1-3 can be represented in the following graphs.

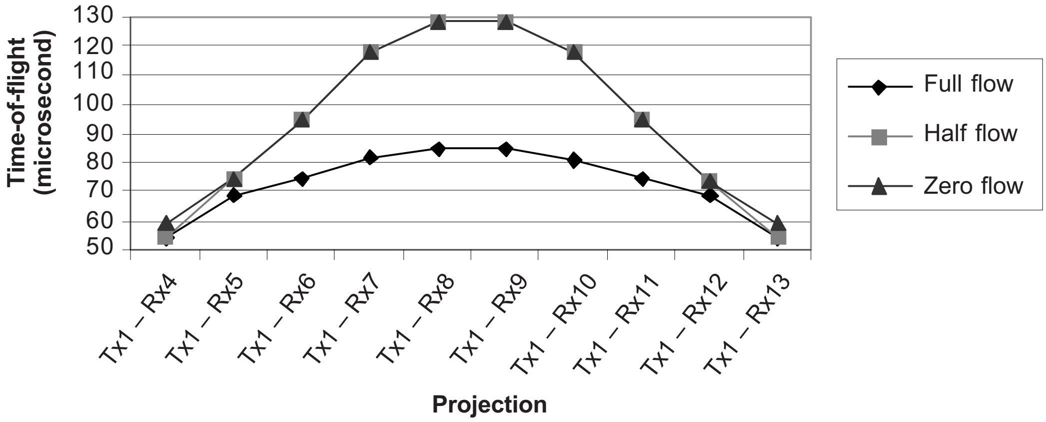

Figure 8 The graph for Time-of-flight versus Projection T×1

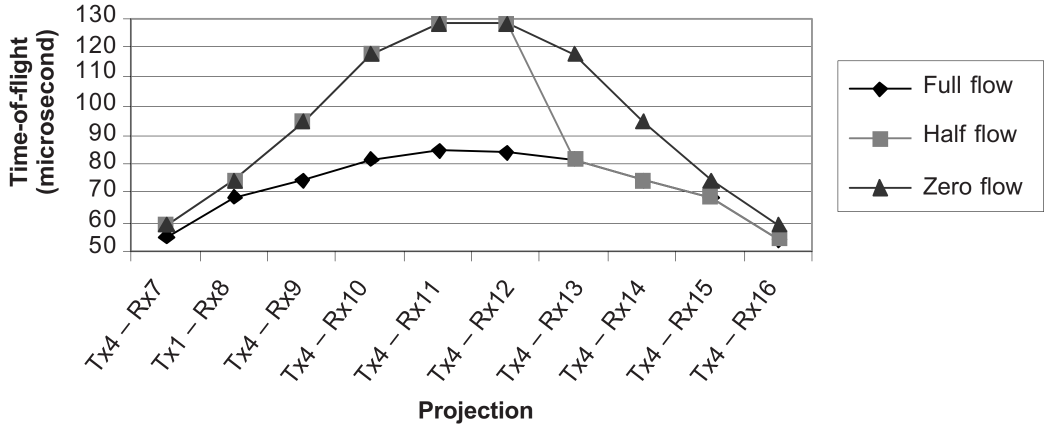

Figure 9 The graph for Time-of-flight versus Projection T×4

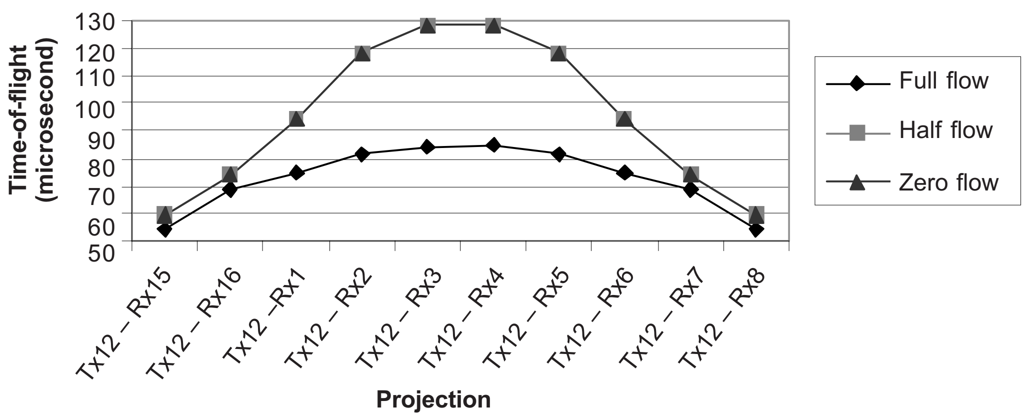

Figure 10 The graph for Time-of-flight versus Projection T×12

The graphs above show that we can easily differentiate the received signals caused by the longitudinal waves and the Lamb Waves. The Lamb Waves will travel a longer distance to the point of interest compared to the longitudinal waves that travel shorter distances by penetrating into the pipe to the point of interest. Thus, the time of observation, (t_s), that lies on the first arrival of the received ultrasonic wave is definitely free from being incorporated by the Lamb Waves and also the reflected waves. By using the sample and hold circuit, it will sample the received ultrasonic signal at t_s and then captured into the PC by using the data acquisition system.

For the image reconstruction, a threshold voltage (V_t) is needed for the purpose of separating the object from the background, thus creating a binary picture from a picture data (tomogram). This procedure is appropriate for two-phase flow imaging in cases where the phases are well separated. If the minimum size zone of any separated phase is larger than the pixel size, the pixel will be wholly filled by one phase. Pixels falling on phase boundaries will be rounded up or down to the nearest phase level. By integrating this thresholding technique with the back-projection algorithm, it is known as the Binary Back Projection Algorithm (BBPA). The binary masking technique is shown as below:

$$\begin{aligned} d &= \{0,\ Vr_{x,\,y} > V_t \\ &= \{1,\ Vr_{x,\,y} < V_t \end{aligned} \tag{1}$$

where d = gas existence, $Vr_{x,\,y}$ = ultrasonic receiver voltage, V_t = threshold voltage

The Binary Back Projection Algorithm then can be used to reconstruct the image of the liquid and gas flow.

7.0 CONCLUSION

An Ultrasonic Tomography System has been developed. This system is an alternative is to the existing flow meters available in the market. Equipped with 16-pairs of ultrasonic sensors, it is hoped that the system could assist in providing better resolution to image reconstruction, in order to provide more accurate liquid and gas flow visualization.

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