Identification of Water/Solid Flow Regime Using Ultrasonic Tomography

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Abstract— **This paper details the development of suitable ultrasonic tomography system that can identify water and solid flow regime. This project presents the application of the ultrasonic tomography in the process and chemical industries. The transmission mode with fan shaped beam projection had been implemented. The system is designing non-invasively that mean the composition in the system can be monitored without disturbing the nature of process in the pipe. The transmission mode for sensing purpose was implemented by using 4 sensors for transmitters and 4 sensors for receivers where 4x4 projections were produced. This project is divided into two parts which are hardware and software. The hardware part is including electronic measurement circuit and fabrication of ultrasonic sensor. Beside, a software part is focusing a coding to microcontroller and circuit design. The data from experimental was analysed and it shows that it can be used to identify water and solid flow regime for ultrasonic tomography application.**

Keywords— **Ultrasonic Tomography, Transmission Mode, Acoustic Impedance, Water/Solid, Non-Invasive**

I. Introduction

In the process and chemical industries, process to flow product in the pipe consists of two phase flow likes liquid and solid. Sometimes, there has an error in the process because of impurities and other things that might be influence the flow of process. To solve the problem, process must be shutdown to maintenance it and it is takes time and high cost. Tomography is the most beneficial technology to solve this problem because installation of ultrasonic tomography system will not disturb the process being examined or it called non-invasive technique.

The transmission mode for sensing purpose was implemented by using four ultrasonic sensors as a transmitter and four ultrasonic sensors as a receiver where 4x4 projections was produced. This project is divided into two parts which are hardware and software. The data from hardware was transfer to oscilloscope to be analyzed.

The author in [1] present about the development of non-invasive ultrasonic tomography for imaging liquid and gas flow. The transmission-mode approach has been used for sensing the liquid or gas two phase flows. Ruzairi in [2] present about the hardware development of ultrasonic tomography system used for monitoring the composition of water and oil flow and the author in [3] present a development of an ultrasonic transmission mode tomography system for the detection small gas bubble using higher frequency ultrasonic sensor.

From recent research, many of researchers did two phase investigation about liquid/gas and water/oil. However, a research for water/solid flow identification is not widely done by researcher. It is because of in a process and oil and gas industries, there is no two phase solid and liquid in vessel was existed and only a small particle solid flow. But in future, it is possible this can be happened in industries.

II. Ultrasonic Tomography System

Ultrasonic waves are high (“ultra”) frequency sound (“sonic”) waves: they vibrate at a frequency above 20 kHz which are too fast to be audible to humans [4]. Ultrasonic devices are used in many fields of measurement, particularly for measuring fluid flow rates, liquid levels and translational displacements.

By using transmission mode and fan shape beam projection technique, the 8 sensors consist of 4 transmitters and 4 receivers were put side by side non-invasively along the periphery of the outer of pipe wall. The fan shape beam geometry firstly introduced by Xu et. al. in 1997 [5]. The fan shape beam is chosen because of the cover area will be bigger for receiver to receive a signal that transmit by transmitter [6]. The sensor arrangement and diverging area for 4 transmitters and 4 receivers sensor arrangement shows in Fig. 1.

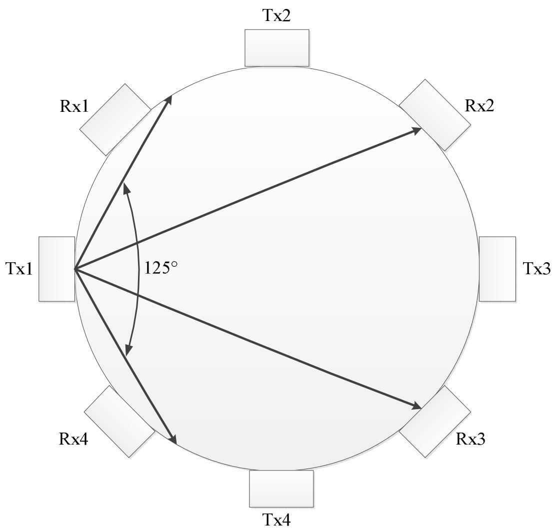

Fig. 1 Sensor arrangement and diverging area

Ultrasonic wave is strongly reflected at an interface between one substance and another. However, it is difficult to collimate and problems occur due to reflections within enclosed spaces, such as metal pipes [1]. There are two types of ultrasonic signals that are usually used by researchers. They are the continuous signal and the pulsed signal [7]. The pulsed system is used to avoid the standing wave patterns that can exist within the pipes.

The popular ultrasonic sensing system is the transmission mode. The transmission-mode technique is based on the measurement of the changed in the properties of the transmitted acoustic wave, which are influenced by the material of the medium in the measuring volume [8]. The change of the physical properties can be the intensity and/or transmission time (time-of-flight) [8]. This approach is assumes straight ray propagation. The projections are collected using separate sending and receiving transducers. There are several interactions are possible. Each projection may comprise the amplitude, phase or time of flight of the signal received.

Acoustic impedance is a term that used to describe the interaction of ultrasound with material [9]. The equation for acoustic impedance, Z is equal to product of density, ρ and the speed of sound, c. The equation given as follows:

$$Z = \rho c \quad (1)$$

If the difference in impedance at the interface is greater, the amount of energy reflected will also be greater [9]. The reflection and transmission coefficient equation as given as follows:

$$\text{Reflection coefficient, } R = \frac{P_r}{P_e} = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1}\right] \quad (2)$$

$$\text{Transmission coefficient, } T = \frac{P_t}{P_e} = \left[\frac{2Z_2}{Z_2 - Z_1}\right] \quad (3)$$

Where P_r is reflected wave sound pressure, P_e is a incident wave sound pressure, P_t is a transmitted wave sound pressure and Z is acoustic impedance.

In this project, a related impedance of materials had been chosen. Table I shows the acoustic impedance of materials.

TABLE I
ACOUSTIC IMPEDANCE OF MATERIALS

Medium	**Material**	**Acoustic Impedance, Z(kg/m²s)**
Experimental column	PVC pipe	3.27 x 10^6
Liquid	Water	1.5 x 10^6
Solid	Steel	45.8 x 10^6
Solid	Ceramics/porcelain	13.4 x 10^6

It is very important to know the ultrasonic propagation in all material. Instead, the reflection and transmission of the ultrasonic propagation between two materials can been known. By presumptuous the ultrasonic energy losses between transducer coupling/PVC pipes are zero, the investigations of ultrasonic wave propagation for such array are described as follow :

A. Ultrasonic Wave Propagation from PVC pipe into Liquid Media

Given that the acoustic impedance of PVC pipe is $Z_1 = 3.27 \times 10^6$ kg/m^2 and for water is $Z_2 = 1.5 \times 10^6$ kg/m^2. By using equation (2) and (3), the calculation of $R_{(PVC/water)}$ and $T_{(PVC/water)}$ can be expressed as

$$R_{(PVC/water)} = \left[\frac{1.5\times10^6 - 3.27\times10^6}{1.5\times10^6 + 3.27\times10^6}\right] = -37.11\% \quad (4)$$

$$T_{(PVC/water)} = \left[\frac{2\times1.5\times10^6}{1.5\times10^6 + 3.27\times10^6}\right] = 62.89\% \quad (5)$$

The negative sign in equation (4) indicates the reversal of the phase relative to the indicate wave. Based on equation (5), it shows that the ultrasonic signal can transmit through PVC and water more than 50%.

B. Ultrasonic Wave Propagation from Liquid into Solid Media(Steel)

The acoustic impedance of water is $Z_1 = 1.5 \times 10^6$ kg/m^2 and steel is $Z_2 = 45.8 \times 10^6$ kg/m^2. Thus, the value of $R_{(water/steel)}$ and $T_{(water/steel)}$ can be expressed as

$$R_{(water/steel)} = \left[\frac{45.8\times10^6 - 1.5\times10^6}{45.8\times10^6 + 1.5\times10^6}\right] = 93.65\% \quad (6)$$

$$T_{(water/steel)} = 100\% - 93.65\% = 6.35\% \quad (7)$$

It shows that almost more than 90% ultrasonic wave will be reflected when it propagates from liquid to solid media.

C. Ultrasonic Wave Propagation from Liquid into Solid Media(Ceramics)

The acoustic impedance of water is $Z_1 = 1.5 \times 10^6\ \mathrm{kg/m^2}$ and ceramics is $Z_2 = 13.4 \times 10^6\ \mathrm{kg/m^2}$. Thus, the value of $R_{(water/ceramics)}$ and $T_{(water/ceramics)}$ are shown as

$$R_{(water/ceramics)} = \left[\frac{13.4\times10^6 - 1.5\times10^6}{13.4\times10^6 + 1.5\times10^6}\right] = 79.87\% \qquad (8)$$

$$T_{(water/ceramics)} = 100\% - 79.87\% = 20.13\%$$
(9)

It shows that almost more than 70% ultrasonic wave will be reflected when it propogate from liquid to solid media.

III. SYSTEM CONSTRUCTION DESIGN

This project consists of hardware system and software system and designed like in Fig. 2. The hardware system consists of ultrasonic sensor setup and electronic measurement setup. The programming for microcontroller unit was implemented in the software system.

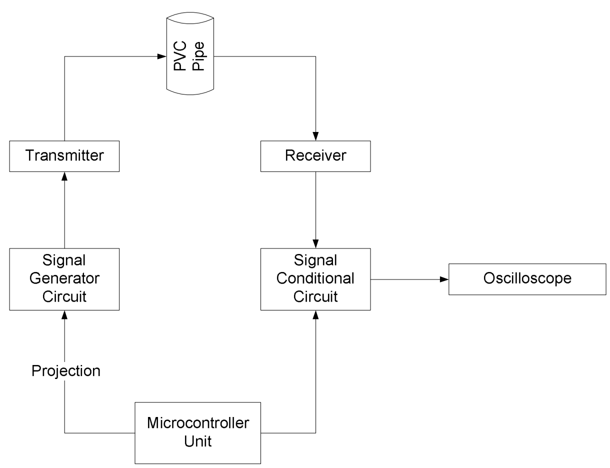

Fig. 2 Ultrasonic tomography system

In this project, a chosen of ultrasonic transducer must have a several criteria such as total beam angle, center frequency, maximum driving voltage and easy to mounting and coupling work. For this project, air ultrasonic ceramic transducer, model 400ET/R080 from Prowave Electronic Corporation was choosen because of its characteristic.

Microcontroller was act as a master controller for the hardware system. The function of microcontroller is to control signal holding circuit, and as a switching circuit for transmitter channel selection for signal generator circuit. In this project, the PIC 16F877A from Microchip Technology was chosen.

For signal generator circuit, the excalibur low noise high speed precision amplifiers or low noise speed op-amp, IC TLE2141CP from Texas Instrument was selected to be implementing as a comparator in the signal generator circuit. The purpose of signal generator circuit is to generate a frequency 40 kHz at every 100 Hz or 10ms delay. Without this delay time, the reverberation effects will totally finish before new excitation is activated and can avoid the overlapping echoes at receiver.

For amplifier part, dual audio operational amplifier, LM833 from Motorola was used because of the high speed op-amp with excellent phase margin and stability. Function of amplifier part is to get voltage gain. It was designed in two stage inverting amplifier with gain for every stage is -33. Thus, it produces a gain with 1089. The value of gain voltage is important in order to keep the signal always in the safety mode. If not, it will influence the signal to clip at positive and negative saturation level.

The software that used for this project are Proteus Professional 7.8 for designing and simulating circuit and PIC C Compiler for programming the microcontroller.

IV. RESULT AND DISCUSSION

The purpose of the experiments is to find out whether there are any changes in the graph in the oscilloscope in term of different materials used. The signals from one transmitter's channel in the corresponding receiver's channel are taken using a digital oscilloscope and being captured to provide a better view during the analysis session. Material used for liquid and solid medium as shown in Table II. The acoustic impedance of PVC pipe that used for this purpose was neglected so that the ultrasonic can penetrate through PVC pipes.

TABLE II
MATERIAL USED FOR THE RESEARCH

Medium	**Material**	**Size (mm)**	**Acoustic Impedance, Z(kg/m²s)**
Liquid	Water		1.5×10^6
Solid	Ceramics/ Porcelain	21 x 14	13.4×10^6
Solid	Steel	19 x 12	45.8×10^6

The solid medium was chosen with different acoustic impedance which gives a different reflection and transmission coefficient. Data for first highest peak voltage and time of flight was shown in Table III and Table IV. Noted that Tx is a transmitter and Rx is a receiver.

TABLE III
DATA FOR FIRST HIGHEST PEAK VOLTAGE

sensor	Water (mV)	Ceramics (mV)	Steel (mV)	Steel and ceramics (mV)
Tx1-Rx2	760	600	520	650
Tx1-Rx3	720	680	500	460
Tx2-Rx3	500	520	440	432
Tx2-Rx4	520	380	300	360
Tx3-Rx1	520	440	520	460
Tx3-Rx4	520	480	400	380
Tx4-Rx1	500	300	300	260
Tx4-Rx2	540	520	520	480

TABLE IV
DATA FOR TIME OF FLIGHT

sensor	Water (µs)	Ceramics (µs)	Steel (µs)	Steel and ceramics (µs)
Tx1-Rx2	99	99	100	100
Tx1-Rx3	100	101	100	163
Tx2-Rx3	105	105	106	110
Tx2-Rx4	101	125	126	125
Tx3-Rx1	108	110	112	110
Tx3-Rx4	108	110	109	111
Tx4-Rx1	109	111	110	155
Tx4-Rx2	110	114	115	111

The data from Table III and Table IV are then represented in the graphs for better analysis. The lowest voltage at Tx4-Rx1 in the graph in Fig. 3 shows that the signal was blocked by steel and ceramics. The nearest reading of steel and ceramics for Tx2-Rx3, Tx3-Rx1 and Tx4-Rx2 with the reading of water shows that no object was blocking the transmitted signal. Graph for steel lower than ceramics because from calculation, steel has a reflection coefficient higher than ceramics which is steel is 93.65% and ceramics is 79.87%. The decreasing of voltage reading shows that the most of the transmitted signal was reflected when there is a medium inside the PVC pipe. The factor changes of voltage are depends on the percentage of reflection coefficient and also a size of materials used.

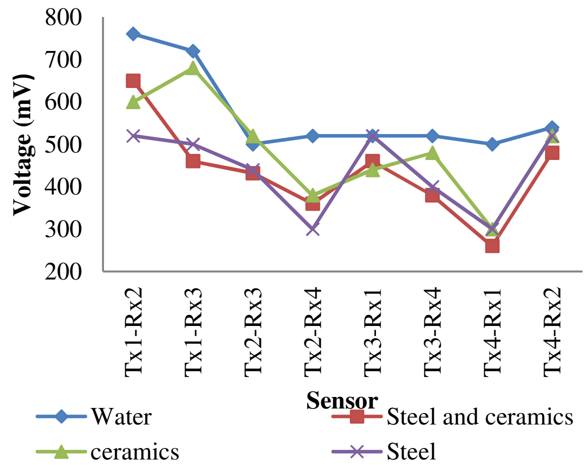

Fig. 3 Graph first highest peak voltage comparison between water with different kinds of materials.

In Fig. 4, the nearest reading of voltage at Tx1-Rx2, Tx2-Rx3, Tx3-Rx1, Tx3-Rx4 and Tx4-Rx2 with the reading of water show that the receiver receives the signal in the straight line from the transmitter although there has obstacle. At Tx2-Rx4 for steel and ceramics, the time is increased because the materials block the signal to transmit in the straight line. So, the signal reflected by the material before it reaches to the receiver. Steel and ceramics for red line graph gave the highest time of flight at Tx1-Rx3 and Tx4-Rx1. This is because the size of steel and ceramics is bigger than single steel and ceramics. It shows that the size of material Influence the reflected of transmission signal many times by pipe wall and materials before reaching to the receiver. The increasing time of flight shows that the transmission signal cannot flow straight to the receiver but it reflects by the material or pipe wall before reach to the receiver.

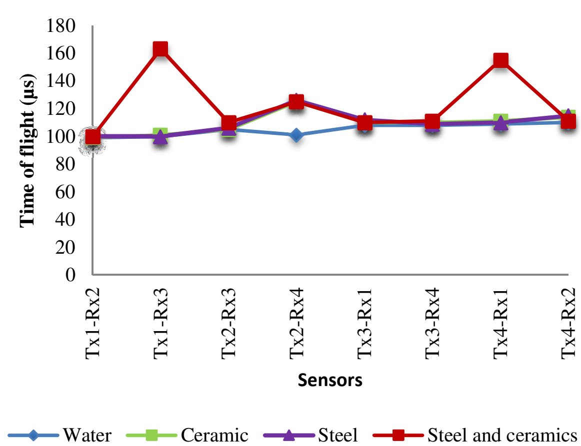

Fig. 4 Graph comparison time of flight between water with different kinds of materials

Beside, by referring Fig. 3 and Fig. 4, it shows that there is a difference between sensors first highest peak voltage and time of flight although no object exists in the pipe. Most probably, this is due to imperfection acoustic coupling that has been attached between the sensor and the outer pipe wall. The most different value is at transmitter Tx1 for first highest peak voltage. Besides, the sensor surface has to keep perpendicular to the pipe wall, so that the transmitted acoustic energy will beam perfectly through the pipe.

From the graphs, it shows that all receivers receive signal from transmitter in various amplitudes and time. The changing amplitude and time depend on location of sensor and medium and also the size of medium. The shape of solid medium also influences the graph because the degrees of reflection signal from solid depend on the shape of the solid. The highest value of first highest peak voltage shows that there is no obstacle block receivers in receiving the signal while the lowest reading shows that there is an obstacle inside the pipe that blocking the receivers from receiving the signals.

Based on the acoustic impedance and calculation of transmission coefficient and reflection coefficient, steel has a higher reflection coefficient compare to ceramics. Then, from the experiment, the different of first highest peak voltage for steel is low and the time of flight for steel is higher than ceramics when it is put inside the pipe. It is because the steel will reflect the transmitted signal higher than ceramics. The different of reading value of water, ceramics and steel show that the ultrasonic tomography system can be used to identify water and solid flow regime.

V. CONCLUSIONS

The objective of this research generally had been achieved. The ultrasonic tomography system used to identify solid and liquid flow is developed successfully. The hardware fabrication of ultrasonic transducer also effectively implemented. Simultaneously, the acoustic impedance of materials and the size of material also affect the value of voltage and time of flight. Thus, it proven that the ultrasonic tomography system is reliable and can be applied in the industries for monitoring the solid and liquid flow.

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