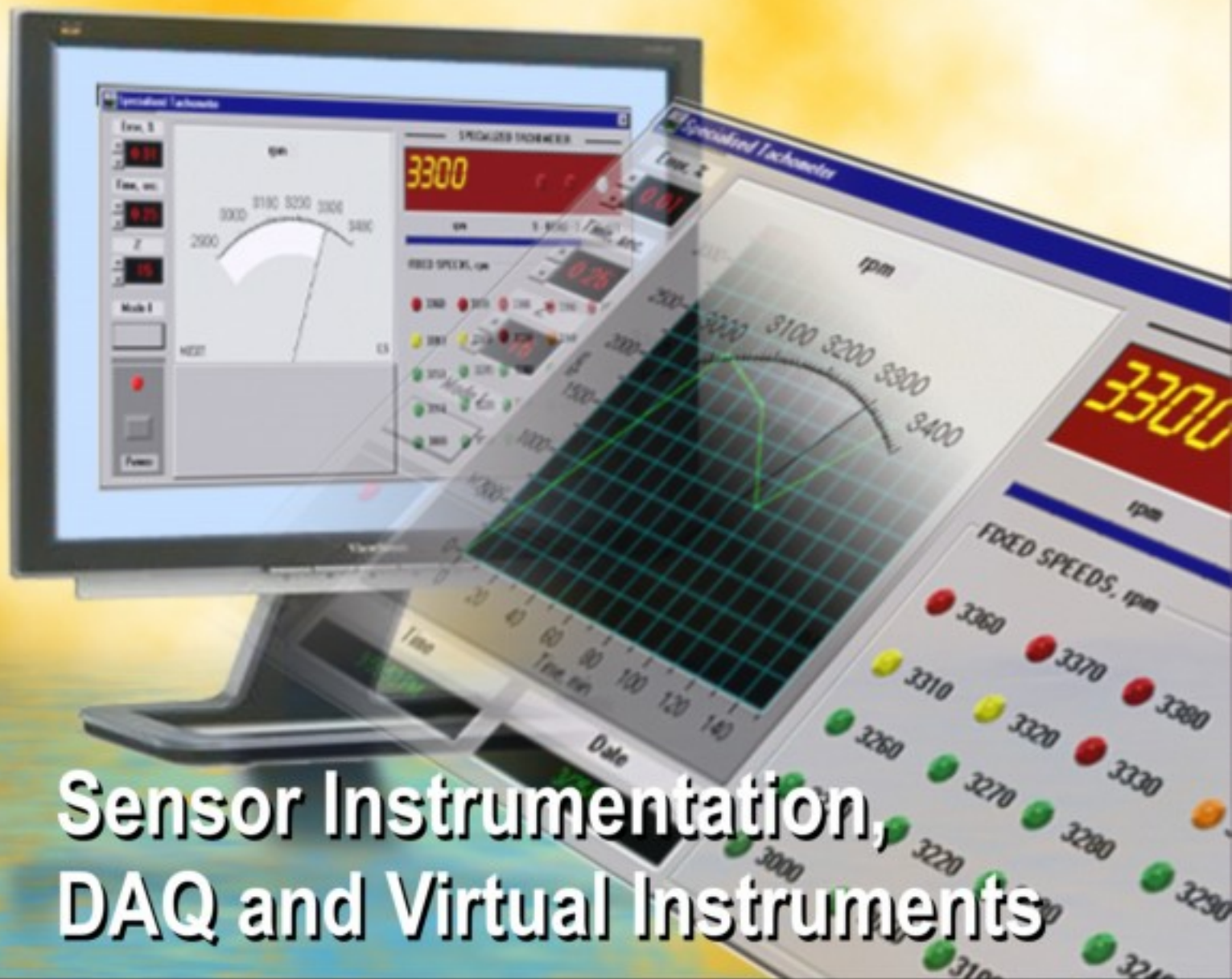


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Hardware Development of Ultrasonic Tomography for Composition Determination of Water and Oil Flow

¹Ruzairi Abdul Rahim, Ng Wei Nyap, ² Mohd. Hafiz Fazalul Rahiman

¹Department of Control and Instrumentation Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia, E-mail: ruzairi@fke.utm.my

²Department of Mechatronics Engineering, North Engineering College University (KUKUM)

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Abstract: A monitoring system for water and oil flow using ultrasonic Tomography is implemented. Information such as the type of flow, the composition of the water and oil can be obtained from the system. The composition of the flow is determined based on the propagation time of the ultrasonic waves. The ultrasonic Tomography system includes the sensors fixture design, signal conditioning circuits and image reconstruction software. The image reconstruction algorithm that used is the Linear Back Projection (LBP) algorithm.

Keywords: Ultrasonic tomography, Image reconstruction, Water and oil, Monitoring system

1. Introduction

The ultrasonic tomography is one of the non-invasive techniques that can be used in the industry for monitoring the flow composition of two liquids flow such as water and oil. The non-invasive method provides the ultrasonic tomography with easy installation and portable convenience. The ultrasonic sensors are very easy to be mounted around the pipeline compared with other sensors. The installation of the ultrasonic tomography system also does not require the shut down of the industry's process. Moreover, this monitoring system does not disturb the internal flow of the pipe. All this benefits support the ultrasonic tomography to be chosen over the other invasive system. It is obvious that the ultrasonic tomography of this research has the potential to contribute to the cooking oil, palm oil and petroleum industries. In this case, the ultrasonic tomography can be applied to determine the composition of the water and oil for the palm oil and the petroleum.

There are several inventions using the ultrasonic techniques for determining the fluid composition that have already obtained the United States Patent such as U.S. Patent 5,473,934 by Cobb (1995), U.S. Patent 4,059,987 by Dowling *et al.* (1977) and U.S. Patent 4,656,869 by Zacharias (1987). However, those inventions required fluid samples taken from the pipelines or predetermined reference data saved in computer. Some of the inventions also used invasive techniques. Most obviously, those

inventions did not display the cross-sectional image showing the composition of the fluid because they were not tomography systems. One of the inventions for monitoring the fluid composition is by Cobb (1995) using ultrasonic non-intrusive technique. Cobb (1995)'s invention involved measurements from the fluid, by which the fluid composition was then determined based on the calibrated data from analytical measurements of fluid samples. Another invention by Urmson *et al.* (1991) was an apparatus for determining the composition of fluid mixture by comparing acoustic travel-time of both changing and reference fluid samples. Invention by Tavlarides *et al.* (1989) was for measuring fractional volumetric holdup in a two liquids phase based on the acoustic velocities. Zacharias (1987) in his invention described a method of measuring the amount of water in crude oil pipeline by extracting a sample from the pipeline. Inventions by Smith (1985) and Dowling *et al.* (1977) were also used for determining the fluid composition that based on measurements of acoustic velocity. In short, those inventions used the same ultrasonic sensors as the ultrasonic tomography system, but the ultrasonic tomography system can display cross-sectional images of the pipeline in real time, determine the fluid composition based on concentration profile, required no samples taken from the fluids and non-invasive.

Ultrasonic testing is based on time-varying deformations or vibrations in material, which is referred to acoustics (Rozenberg, 1973). All material substances are comprised of atoms, which may be forced into vibration motion about their equilibrium positions. Acoustics is focused on particles that contain many atoms that move in unison to produce a mechanical wave. If the material is not stressed in tension or compression beyond its elastic limit, its individual particles will perform elastic oscillations. When the particles of a medium are displaced from their equilibrium positions, internal forces arise. It is these elastic restoring forces between particles, combined with inertia of the particles that leads to oscillatory motions of the medium.

In solids, several types of wave propagation can occur that are based on the way the particles oscillate. Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing. In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation. Longitudinal waves can be generated in liquids, as well as solids because the energy travels through the atomic structure by a series of compression and expansion movements.

In the transverse or shear wave, the particles oscillate at a right angle or transverse to the direction of propagation. Shear waves require an acoustically solid material for effective propagation and, therefore, are not effectively propagated in materials such as liquids or gasses (Rozenberg, 1973). Shear waves are relatively weak when compared to longitudinal waves. The kind of waves that involved in this system is the longitudinal wave as the flow medium is comprised of liquids. The measurement involved the propagation time of the ultrasonic wave.

2. Ultrasonic Time of Flight Method

Ultrasonic sensor is a kind of non-destructive sensor and has been successfully applied in process measurement particularly in flow measurement (Williams, 1995). There are three sensing modes of ultrasonic Tomography which are transmission, reflection and diffraction sensing modes.

The method that applied in this research is the transmission method. In this method, the propagation time of the ultrasonic wave from the transmitter to the receiver through the medium will be measured. The velocity of the ultrasonic wave varies in different mediums. Different composition of two liquids such as water and oil will also show different propagation time of ultrasonic wave. By finding the difference of this propagation time, ultrasonic Tomography could be applied for the flow monitoring purpose. In ultrasonic Tomography, the required equipments include ultrasonic generator, transducers to transmit and receive ultrasonic waves as well as computerized image-processing system.

3. Hardware Implementation

The Figure 1 below shows the layout design of the ultrasonic Tomography system. There are 16 pairs of transmitters and receivers mounted non-invasively around the pipe. The diameter of the pipe used is 100mm. The flow inside the pipe is a mixture of water and oil. The composition of the flow that varies from time to time is monitored by this system.

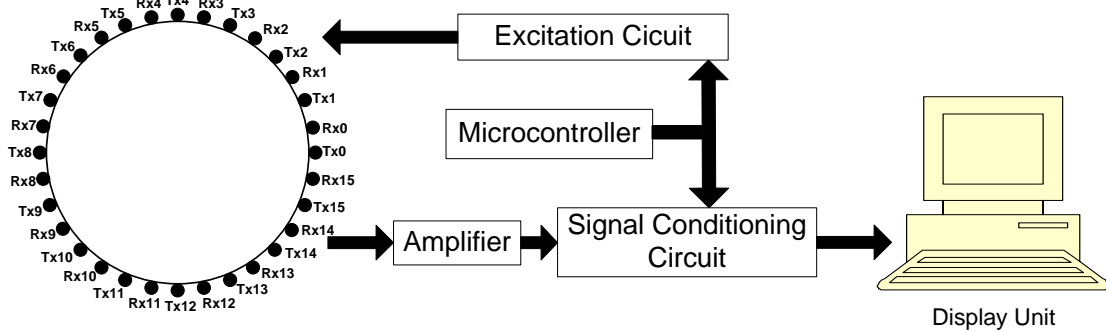


Fig. 1. Layout design of ultrasonic tomography.

3.1 Selection of Transmitter and Receiver

The ultrasonic sensors that are used in the project are the closed face piezo-based transducers with 40 kHz of its frequency and beam angle of 125° . This type of sensors is chosen because it is not expensive and the penetration power of the ultrasonic sensor is already enough for transmitting the ultrasonic waves through the pipe. However, the most important factor is that the ultrasonic sensors have a wide angle of 125° which can provide a wide visualization area.

Beam angle is an important consideration in ultrasonic sensors selection. It defines how wide the beam can spread and cover an area. Beam angle is largely determined by the frequency and diameter of the transducer. A high frequency transducer produces a narrow beam. A low frequency produces a wider beam. As the diameter of the transducer increases, the beam spread will be reduced. The beam angle of the ultrasonic sensor for this project is 125° typical. Therefore, the ultrasonic waves can cover the opposite 10 receivers as illustrated in Figure 2.

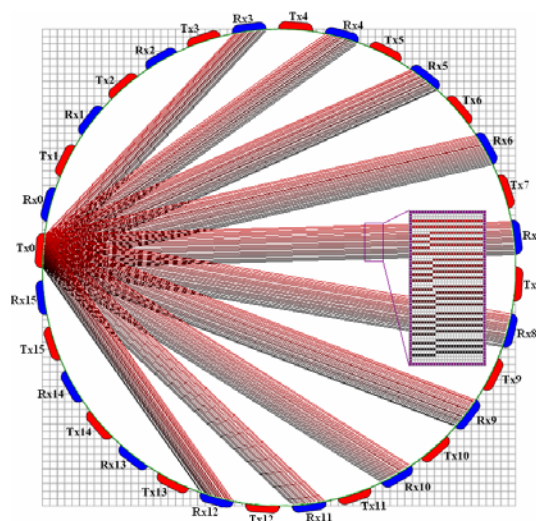


Fig. 2. Path modeling of ultrasonic waves.

3.1.1 Mounting of Ultrasonic Sensor

The grease is used as the coupling material in this project as the acoustic impedance matching between the ultrasonic sensors and the acrylic pipe. This is important to maintain the penetration power of the ultrasonic waves from the transmitter to the receiver through the pipe. The grease is used to make sure that there is no air trapped between the ultrasonic sensors and the pipe because the ultrasonic waves suffer a great loss of transmission power in the air. Moreover, the grease also is non-corrosive, non-toxic, high viscosity and inexpensive. Dry contact will not do, because in reality it means actual contact only at a very few points and everywhere else there is an air-filled gap, impenetrable to ultrasonic waves. The thickness of the grease used in the project is almost 1 mm. The ultrasonic sensors are clamped firmly around the pipe by a clamping ring. Figure 3 below shows the mounting technique of the ultrasonic sensor on the acrylic pipe. Figure 4 shows the mounting and clamping of ultrasonic sensors in the project.

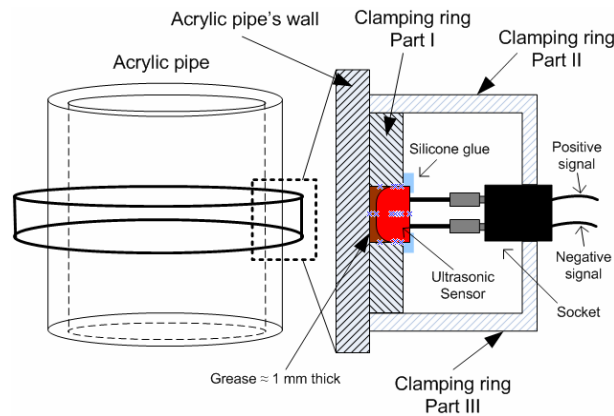


Fig. 3. Mounting technique of ultrasonic sensor.

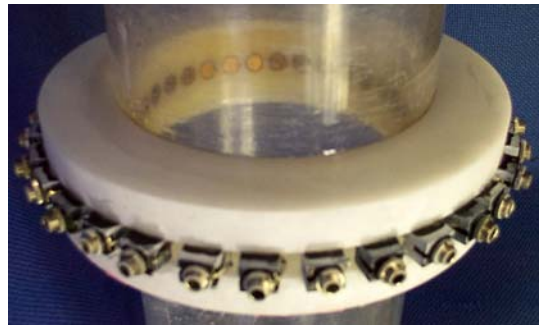


Fig. 4. Mounting of ultrasonic sensor.

As shown in Figure 4, there are 32 ultrasonic sensors mounted non-invasively around the acrylic pipe. The acrylic pipe is chosen because it is transparent and the condition of the flow inside could be observed.

3.2 Design of Transmitter Circuits

Basically, the transmitter circuits or excitation circuits consist of a switching circuit and a driving circuit. Pulses will be generated to excite the transmitter so as to transmit the ultrasonic waves that can penetrate through the pipe and the medium, which are then received by the receivers.

3.2.1 Switching Circuit

The switching circuit is microcontroller based that control which transmitter transmits first, the width of the excitation pulse, the pulse repetition frequency and the reverberation time. The microcontroller chosen is PIC18F458, a product from Microchip Company. This microcontroller, PIC18F458 is chosen because its program is easy to be learnt, its speed and the number of its I/O pins also meet the requirements of the project. The microcontroller is chosen as the switching circuit over the other circuits which may be counter based, because of its timing adjustment flexibility and timing accuracy. The execution of one instruction cycle of the microcontroller requires four clocks.

The time of one instruction cycle, T_{cy} of 100 ns is enough for the time resolution of the switching control for the transmitter channel. Basically, the switching circuit consists of a microcontroller, a decoder and four inverters.

The sequence of the transmitter to transmit the ultrasonic wave, the repetition frequency, the width of the excitation pulse and the reverberation time are all controlled by the microcontroller. The transmitter channel is disabled to provide the required reverberation time to make sure that the ultrasonic waves in the flow dies down before a new pulse is transmitted.

3.2.3 Driving Circuits

The driving circuits are used to increase the magnitude of the pulses that excite the transmitters so that ultrasonic waves with higher penetration power can be transmitted. The pulses from the switching circuit with magnitude of 5V are converted to pulses with amplitude of 30 V_{p-p}. Each ultrasonic transmitter is connected to one driving circuit, so there are 16 driving circuits in total. Figure 5 below shows the schematic of the driving circuit for transmitter channel 0, Tx0.

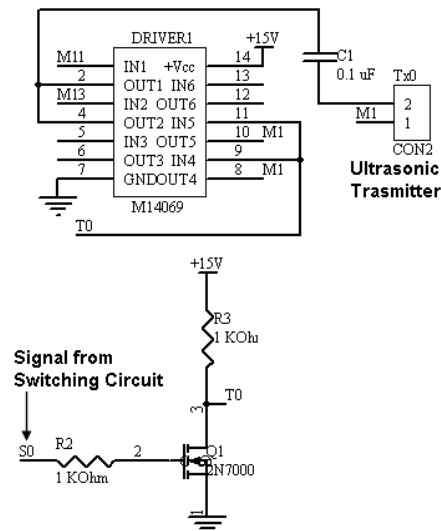


Fig. 5. Driving circuit for ultrasonic transmitter.

The ringing effect is caused by the diaphragm of the ultrasonic sensor is still vibrating although the pulse signal has stopped. However, it does not bring any effect to the transmitter because the vibration of the diaphragm of the ultrasonic sensor has stopped before the diaphragm of the ultrasonic transmitter start to vibrate again due to another pulse signal.

3.3 Design of Receiver Circuits

The receiver circuits consist of amplifier circuits, zero-crossing detector circuits, signal holding circuits, binary counters and buffers. Basically, the purpose of the receiver circuits is to receive and measure the time of flight of the ultrasonic waves.

3.3.1 Amplifier Circuits

The operational amplifier, LF356 is used to implement the inverting amplifier circuit. Two inverting amplifiers are cascaded to get a higher amplification gain. The ultrasonic receivers are connected directly to these amplifier circuits.

Figure 6 shows the schematic of one of the inverting amplifier circuits that is connected to the receiver, Rx0.

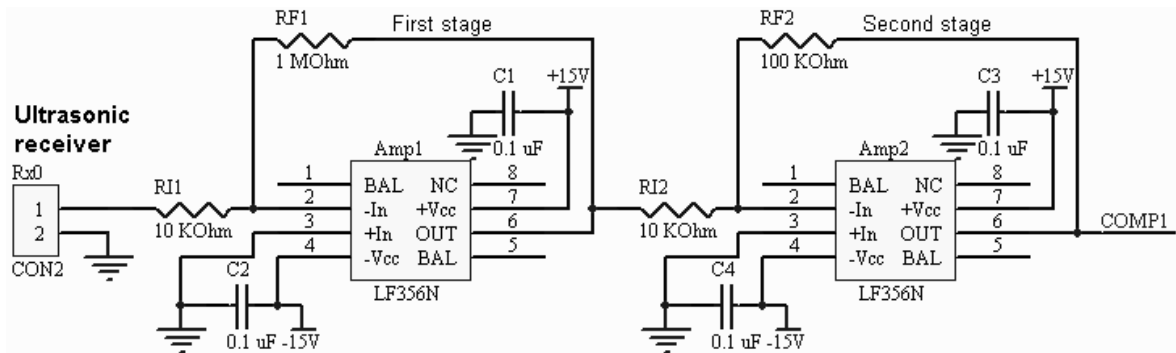


Fig. 6. Inverting amplifier circuit.

The signals that are received by the amplifier circuit will be amplified with the gain of 100 at the first stage and the gain of 10 at the second stage. Therefore, the total amplification gain is 1000.

3.3.2 Zero-Crossing Detector Circuit

Ideally, a zero-crossing detector is a comparator that compares signals with reference to the ground (0 V). When the input signal is more than 0 V, the zero-crossing detector will produce a logic high output. However, in reality, due to the noises from the circuit and the surrounding, the reference voltage of the zero-crossing detector is set to 1.67 V, instead of 0 V. This is to avoid the zero-crossing detector from producing a logic high output if there are noises in the received signals that are more than 0 V. Figure 7 shows the circuit of the zero-crossing detector that used in the project.

In order to optimize the high speed performance, a 0.1 μ F capacitor is placed as close as possible from the power supply pins to the ground. These capacitors act as charge reservoirs for the zero-crossing detector during high speed switching. Figure 8 shows the signals from the zero-crossing detector.

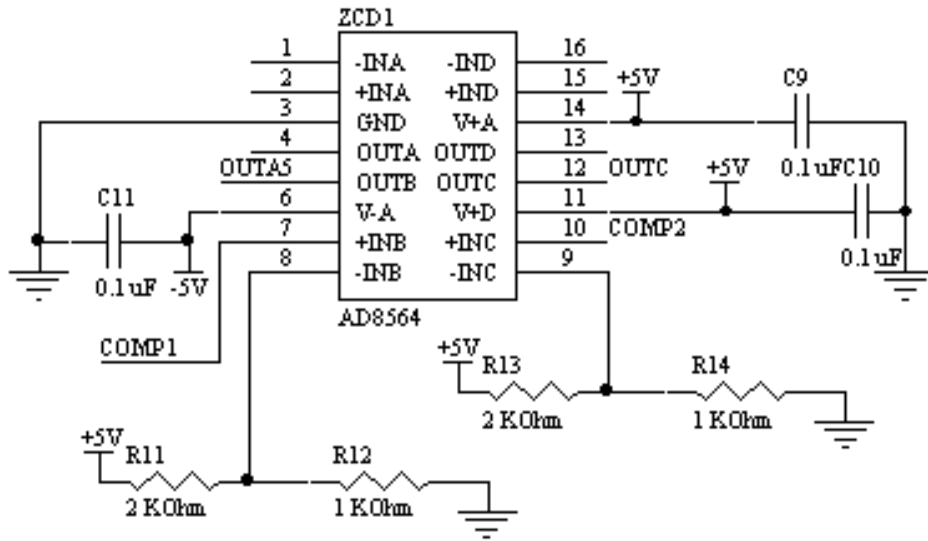


Fig. 7. Zero-crossing detector circuit.

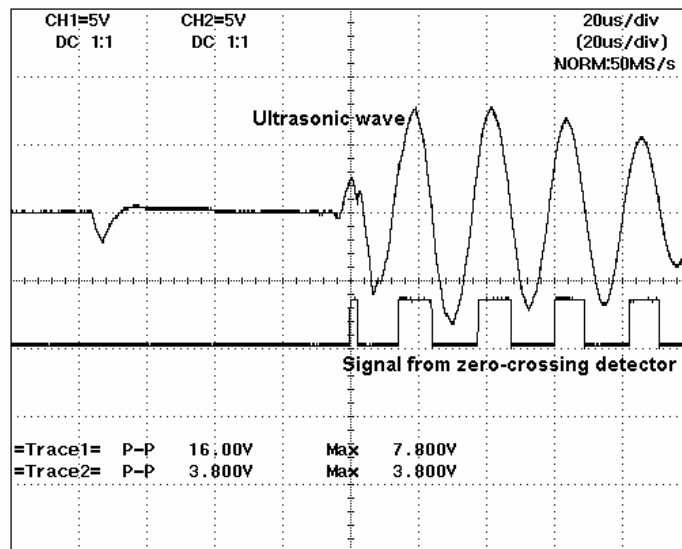


Fig. 8. Signal from zero-crossing detector.

3.3.3 Signal Holding Circuits

The function of the signal holding circuits are to detect and hold the first arrival signal from the zero-crossing detector during each transmit cycle. The binary counter will stop counting when the first arrival signal is detected. Therefore, the propagation time of the ultrasonic waves could be measured by using this method. The signal holding circuits consist of a NAND gate and a \bar{S} - \bar{R} flip-flop latch as shown in Figure 9.

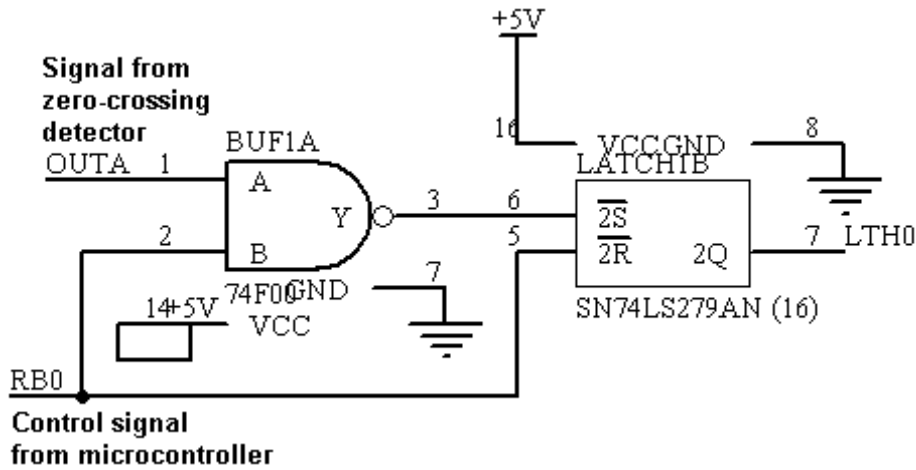


Fig. 9. Signal holding circuits.

3.3.5 Buffer

It is used to drive the signals to the data acquisition system (DAS) card. It also provides a means of isolating the signals from the hardware circuits with the DAS card.

3.3.6 Crystal Oscillator

The crystal oscillators that used in the project to provide the clock to all the sixteen binary counters and the microcontroller are the quartz crystal oscillators with the frequency of 40 MHz. Each crystal is connected as close as possible to each binary counter and microcontroller to reduce noises that may occur. Noises should be avoided as the clock with frequency of 40 MHz is very high speed and sensitive to noises. The output of the crystal is universal output HCMOS and TTL compatible.

3.4 Master Controller

Besides acting as a switching circuit for the transmitter channel selection, the microcontroller also acts as a master controller that controls the zero-crossing detector circuits, signal holding circuits, reset of binary counters and function of the data acquisition system (DAS) card.

The microcontroller plays an important role to coordinate all the signals to make sure that the measurements are taken correctly and captured into the computer by the DAS. Therefore, the timing for all the control signals is very important to make sure the whole system is executing correctly and in order. Without the coordination of the microcontroller, the measurement of the receivers will be wrong and the flow monitoring system cannot be performed. Figure 10 below shows the timing diagram (drawn without a scale) of the microcontroller.

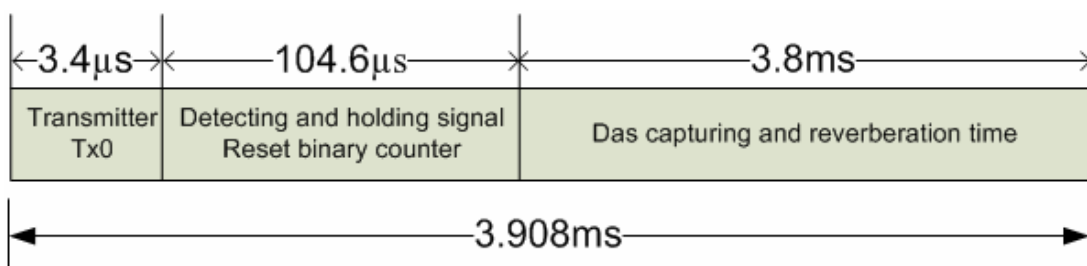


Fig. 10. Timing diagram of microcontroller.

Figure 10 only shows the timing diagram from when the transmitter Tx0 starts transmit the ultrasonic waves until the measurements for the transmitter Tx0 captured by the DAS. The timing goes the same with the other transmitters with transmitter Tx1 starts to transmit after that, and transmitter Tx15 is the last to transmit the ultrasonic waves. Each transmitter will be triggered by a pulse of 3.4 μ s wide to transmit the ultrasonic waves. After that, the reset of the binary counter, the detecting and holding of the first arriving signals will be done within 104.6 μ s. The ultrasonic waves arrive at each receiver at different times. However, the ultrasonic waves will arrive within 104.6 μ s after transmitted. After that, the DAS will capture the measurements from every binary counter. Certain delay time is also allocated for the reverberation of the ultrasonic waves. This is to make sure that all the ultrasonic waves in the flow already die down before a new pulse is transmitted. The total time for the DAS operation and reverberation time is 3.8 ms. Therefore, the time of the measurements captured for a single transmitter is 3.908 ms. The total time for a complete execution of all the transmitter channels is 3.908 ms x 16 = 62.528 ms. The repetition frequency of the microcontroller is therefore 16 Hz.

Therefore, the achievable sampling rate from the hardware circuits is 16 *f/s* (frame per second). However, the rates of the image reconstruction will less than this sampling rate because of the delay time in circuits and the software execution.

The ultrasonic transmitters and receivers are connected to the hardware circuits using coaxial cables to reduce the noises and prevent electrical interference from the environment. The data acquisition system (DAS) card used, which is computer compatible PCI bus, is a product from ICP DAS Inc.

4. Results and Discussion

The tomograms for the dual segment flow of the oil share the similar view in the project. The tomograms show that the percentage of oil is increasing while the percentage of water is decreasing from tomogram. The oil component is represented by red color while the water component is represented by blue color from the color scheme.

As can be seen from the 10 tomogram Figure 11 the water component and the oil component can be seen and recognized clearly. It can be seen that the oil which is represented by red color, is floating on the water which is represented by blue color. The oil component is increasing while the water component is decreasing. The color scheme used and the image enhancement technique improve the visualization of the tomogram for water and oil flow.

5. Conclusions

The ultrasonic tomography system used for monitoring the composition of water and oil flow is developed successfully. The design of the transmitter circuits is to transmit the ultrasonic waves while the design of the receiver circuits is to measure the delay propagation time of the receiver circuits. Measurements from the receiver circuits are captured into the computer by using the DAS card. The measurements from the hardware system must be correct before the cross-sectional image can be reconstructed by the software system. The ultrasonic tomography system can provide information for the water and oil composition of the flow based on the concentration profile.

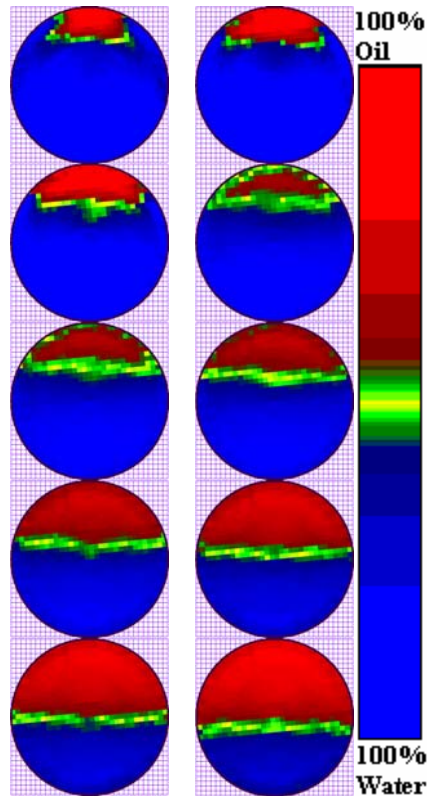


Fig. 11. Tomogram of Corn Oil (I).

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726- 5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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