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Small Gas Component Detection using Ultrasonic Transmission-mode Tomography System

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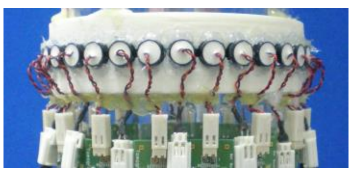
Graphical abstract



Abstract

This paper presents the development of an ultrasonic transmission-mode tomography system for the detection of small gas components by using higher frequency ultrasonic transducers. The selection of the transducer is important and must be suitable to the application design. Consideration on the natural limitation of ultrasonic wave is also noted as the higher the frequency of the ultrasonic transducer, the better the sensitivity but lower penetration depth. 16-pairs of these ultrasonic sensors are installed and fixed inside a sensor jig which is designed to hold all the sensors while providing support for optimum angle sensor placement. The sensor jig is also mounted on the circumference of a vertical column which will be used as the investigated process vessel. The developments presented also include the non-invasive fabrication techniques, the electronic measurement circuits, image reconstruction technique, and finally on the imaging results of the proposed system.

Keywords: Ultrasonic tomography; transmission-mode; ultrasonic sensor; liquid/gas imaging

■1.0 INTRODUCTION

Process monitoring plays an important role in most areas such as in industries and research field. Widespread need for the monitoring of the internal activities of process plants arises to further improve the design and operation of the process plant. Thus, process tomography has the requirements of providing the solutions on the need of such monitoring system with the advantage of providing quantitative data of the internal behavior without disrupting the process plant [1].

Ultrasonic Tomography has the advantage of providing a monitoring system able to reconstruct the distribution of a gas/liquid two-phase flow over the cross-section of a pipe while being non-invasive and possibly non-intrusive to the corresponding activities inside the column [2]. The system can be used for the measurement of two-component flow such as liquid or oil flow through a pipeline or any process vessel which is increasingly of importance in many industrial processes (e.g. oil exploration, flow behavior monitoring, turbulence control, chemical process monitoring, chemical mixing etc). Wide range of applications can benefit by the use of Ultrasonic Tomography.

Detection of bubble is also a requirement in many industrial applications which includes filling operations in the paint, detergents, food, cosmetics and pharmaceutical industries where bubble may degrade the product [3]. Optimizing the harvesting process and transportation in petrochemical industry also requires the detection of bubble. Gas which had dissolved into the crude in the high pressure at the well base resolves as the crude is brought up to surface pressure. Bubble detection in the bore may warn of high-pressure gas pockets. In hydroelectric stations, bubble detection gives warning of cavitation [4].

Ultrasonic bubble detection has other industrial applications, including fluid processing, pressure measurement, and pressure vessel monitoring. Medical applications include studies of decompression sickness, and contrast echocardiography. Bubble in vivo can be detected actively and passively.

A bubble in liquid will in general contain a mixture of permanent gas and vapor [5] and will be approximately stable over timescales where dissolution and buoyancy may be neglected if the partial pressure of the gas component roughly counterbalances the constricting pressure due to surface tension and the pressure in the surrounding liquid (which may consist of acoustic or hydrodynamic pressure perturbations superimposed upon a hydrostatic field). An acoustic field can drive it into nonlinear pulsation (termed 'stable cavitation'), which at small amplitudes of freedom linear oscillator. Shape and surface oscillations may also occur, and may be associated with micro streaming flows about the bubble [4].

This clearly shows that there is a widespread need for the direct analysis of the internal characteristics of the process plant in order to improve the design and operation of equipment in various industries. The measurement of two-component flow such as liquid or oil flow through a pipe is increasingly important in many applications and it is proven that the operation efficiency of such process is closely related to accurate measurement and control of hydrodynamic parameters such as flow regime and flow rate [1].

■2.0 IMPORTANCE OF THE ULTRASOUND WAVELENGTH IN DETECTING SMALL DISCONTINUITY

The wavelength of the ultrasound wave is related to its velocity and frequency by the standard relationship:

$$\lambda = \frac{c}{f} \tag{1}$$

where,

λ = ultrasonic beam wavelength.
c = speed of sound.
f = ultrasonic frequency.

The wavelength is directly proportional to the velocity of the wave and inversely proportional to the frequency of the wave. This relationship is shown in Equation 1 where in a given material increasing the frequency may be expected to increase the sensitivity of the system.

Objects which are smaller than the wavelength of the ultrasonic beam will neither block nor reflect the acoustic pressure wave, but will diffract it instead [6]. Thus by using ultrasonic wave for imaging process, the shorter wavelength resulting from an increase in frequency will usually provide for the detection of smaller discontinuities.

The wavelength of the ultrasound used by the system has a significant effect on the probability of detecting small discontinuity. A general rule of thumb is that a discontinuity must be larger than one-half the wavelength to stand a reasonable chance of being detected by the system [7]. Small gas bubbles which are smaller than half a wavelength (λ/2) will not necessarily reflect energy back to the source. They may reflect energy back, but this is not a certainty.

Hence it is postulated that the smallest gas bubble one can pick up with a certain wavelength is λ/2. Thus an ultrasonic beam having a center frequency of 333 kHz can be used to detect small gas bubbles in water with a diameter bigger than 2.25 mm.

■3.0 FRONT-END HARDWARE CONFIGURATION

Designing the front end of an ultrasonic tomography system is among the most important parts; one can say that they are the eyes and ears of the system. This includes mounting the 16-pairs of ultrasonic transmitters and receivers which is considered as the sensing area (
Figure 1) for the ultrasonic tomography system. Associated electronic measurement circuits are then designed to process the output from the sensing area.

This is important for acquiring the data needed to produce a meaningful image. This 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 the front end of an acoustic imaging system should be regarded as a first priority [8].

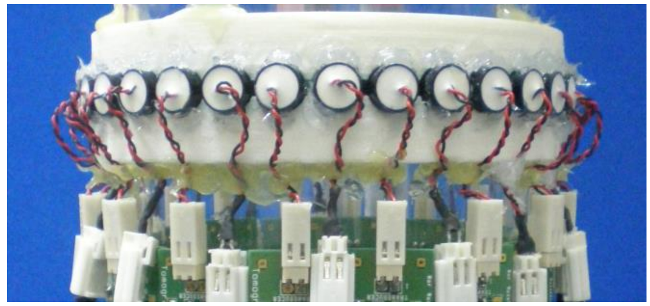


Figure 1 Sensing area consists of 16-pairs of ultrasonic transducers

The success of all acoustic imaging systems lies in matching the properties of the imaged objects with the related characteristics of ultrasound. In practice, if an ultrasonic transducer is placed against the surface of a material, very little ultrasonic energy will actually enter the material. This is because a very thin air layer will usually exist between the face of the transducer and the surface of the material. Air, being a very poor conductor of sound energy, will prevent effective coupling of the transducer to the material [7].

For this reason, a high-grade grease is used by the sensing area as the acoustic coupling to obviate gas components when mounting the ultrasonic transducers on the circumference of the pipe's wall as shown in Figure 2. Acoustic couplant placement will also significantly help to maximize the transmitted acoustic energy to the corresponding ultrasonic receivers.

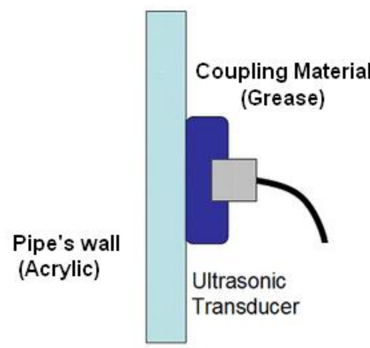


Figure 2 Acoustic coupling placement for ultrasound transmission

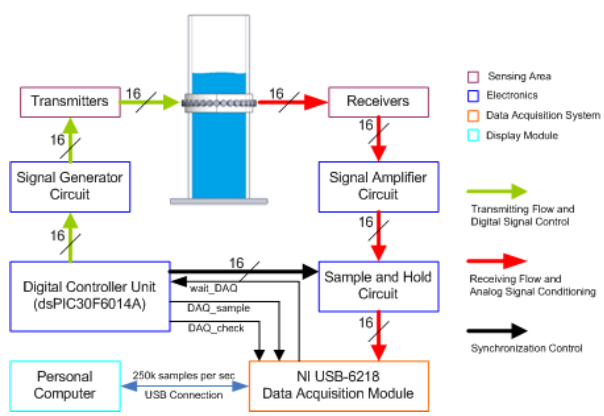


Figure 3 Electronics circuitry and the embedded system used in the Ultrasonic Tomography System

4.0 ELECTRONIC AND SIGNAL PROCESSING CIRCUITRY

Generally, the design of an ultrasonic tomography system is divided into 4 small parts: 1) sensing area, 2) electronics, 3) data acquisition system and 4) display module. As have been introduced earlier, the sensing area is made up of 32 ultrasonic transducers which are each paired with their own corresponding to form 16-pair of ultrasonic transmitters and receivers. The other electronic and signal processing circuits are as shown in
Figure 3.

4.1 Pulse Generator Circuit

The Pulse Generator Circuit (Figure 4) is a simple ultrasonic transmitter circuit that uses Operation Amplifier (op-amp) as a comparator. The op-amp used is TLE2141 from Texas Instruments (TI).

The TLE2141 op-amp that is used as a comparator operates without negative feedback. When the non-inverting input (V+) is at a higher voltage than the inverting input (V-), the high gain of the op-amp causes it to output the most positive voltage it can. When the non-inverting input (V+) drops below the inverting input (V-), the op-amp outputs the most negative voltage it can. Since the output voltage is limited by the supply voltage, for an op-amp that used a single supply (powered by 0 to +15V) this action can be written [9]:

$$V_{out} = \begin{cases} V_{supply+}\,, & (V+ > V-) \\ V_{supply-}\,, & (V+ < V-) \end{cases} \tag{2}$$

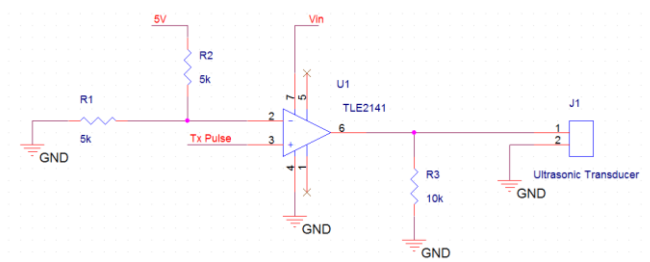


Figure 4 Pulse generator circuit schematic

4.2 Signal Conditioning Circuit

Appropriate low-noise signal conditioning circuit is used for the hardware development. The signal conditioning circuit purpose is to filter DC signals and amplify the received ultrasound energy.

The initial value from the ultrasonic receivers are fairly small which makes it hard to differentiate the voltage readings for different conditions, thus for the system to read its signal, the signal conditioning circuit are designed to amplify the receiving signals.

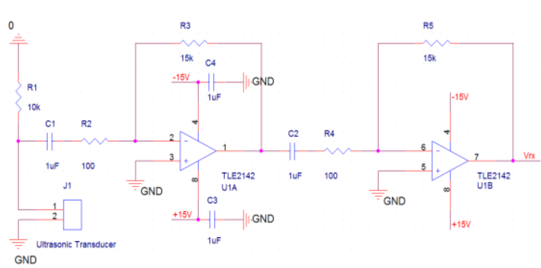


Figure 5 Signal conditioning circuit

As shown in Figure 5, two Operational Amplifiers (Op-Amps) are used to construct a 2-stage inverting amplifiers that will significantly increase the magnitude of the input signals from the ultrasonic transducer. Both stages have a gain of -150 as shown in the calculation below:

$$A_{1st\ stage} = -\frac{R_3}{R_2} = -\frac{15000}{100} = -150$$
$$A_{2nd\ stage} = -\frac{R_5}{R_4} = -\frac{15000}{100} = -150$$

Since multiple amplifiers are staged, their respective gains form an overall gain equal to the multiplication of the individual gains.

$$\begin{aligned} A_{total} &= A_{1st\ stage} \times A_{2nd\ stage} \\ &= -150 \times -150 \\ &= 22{,}500 \end{aligned}$$

Therefore total gain of the chain of cascaded amplifiers used in this research to increase the input signal of the receiving ultrasonic transducer is 22,500.

The signal after it is amplified is in continuous time. A sample and hold circuit is used to interface real-world signals, by changing analogue signals to a subsequent system such as an analog-to-digital converter. The purpose of this circuit is to hold the analogue value steady for a certain period of time. A capacitor is used to store the analogue voltage and digital switching is used to alternately connect and disconnect the capacitor from the analogue input.

The Sample and Hold Circuit using the LF398N IC from National Semiconductor are used to input the AC signal from the ultrasonic receiver signal and output the DC voltage value of the sampled ultrasonic input (
Figure 6). The DC values are then used to determine the strength of the transmitted ultrasound signal.

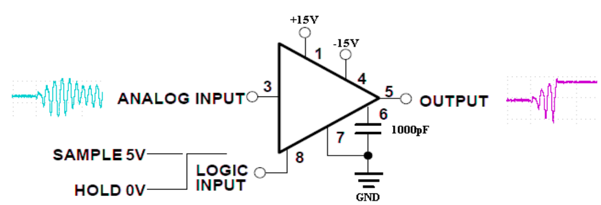


Figure 6 Typical sample and hold circuit

Choosing the capacitors for use in a Sample and Hold circuit as the hold capacitor is very important. The most important characteristic to observe for when choosing capacitors for use in this application is their Dielectric Absorption (DA) ability. The hold capacitor used is from Polypropylene type as they have low DA.

Recommended capacitors for this type of application include the "poly" type capacitors, i.e., polystyrene, polypropylene or Teflon. These capacitor types have very low dielectric absorption (typically <0.01%).

The hold capacitor used for the Sample and Hold circuit for this project have a capacitance dielectric type of Polypropylene as they have the advantages such as low DA available (typically 0.001% - 0.02%), inexpensive and are available in wide range of values. However their most disadvantages is that they have large case size and can be damaged in an environment with high temperature (more than 105°C) [10].

4.3 Data Acquisition Module

The data acquisition system was used as the analogue-to-digital converter (ADC) with programmable input/output ports for synchronizing the software protocol between GUI control from the computer and the hardware system. Therefore, the National Instruments NI USB-6218 is chosen to perform the data acquisition from the hardware system into the PC.

5.0 IMAGE RECONSTRUCTION ALGORITHMS

The back projection algorithm is the first analytic method to perform image reconstruction from projection signals in medical X-ray tomography [9,11]. There are a few variations of the back projection algorithm such as linear back projection, filtered back projection, convolution back projection and graphical back projection algorithms. The linear back projection (LBP) algorithm is chosen to be implemented in this research.

Most of the work in process tomography has focused on the use of Linear Back Projection (LBP) algorithm. It is originally developed for the X-ray tomography and it also has the advantages of low computation cost. The LBP is computationally straightforward to implement and is a popular method for image reconstruction. Sensitivity maps which were derived for the individual sensors are used by the LBP algorithm to calculate concentration profiles from measured sensor values [12]. The process of obtaining concentration profile using LBP can be expressed mathematically as follow [9]:

$$V_{LBP}(x,y) = \sum_{Tx=0}^{m} \sum_{Rx=0}^{n} S_{Tx,Rx} \, x \, \bar{M}_{Tx,Rx}(x,y) \qquad (3)$$

where,

$V_{LBP}(x,y)$ = voltage distribution on the concentration profile matrix
$S_{Tx,Rx}$ = the sensor loss value
$\bar{M}_{Tx,Rx}(x,y)$ = the normalized sensitivity matrices

Eminent Pixel Reconstruction (EPR) is another image reconstruction algorithm proposed in this paper which is based on the previous development by Sallehuddin [13]. This algorithm determines the condition of the concentration profile and improves the reconstruction mechanism by passing the high intensity pixels post reconstruction.

The algorithm masks the reconstruction process of LBP algorithm with binary values. If the pixel value equals or less than the concentration threshold pre-set, the final pixel values are set to zero. Using the signal loss measurement approach, the pixels with high intensity values also termed as the eminent pixels are better highlighted by adopting EPR algorithm (Equation 4 and 5) into the system [9]. Mathematical model for EPR are shown as below:

$$B(x,y) = \prod_{Rx}^{16} \prod_{Tx}^{16} Z_{Rx,Tx} \begin{cases} Z_{Rx,Tx} = 1 & S_{Rx,Tx} > P_{Th} \\ Z_{Rx,Tx} = 0 & S_{Rx,Tx} \leq P_{Th} \end{cases} \qquad (4)$$

$$V_{EPR}(x,y) = B(x,y) \times V_{LBP}(x,y) \qquad (5)$$

where,

$B(x,y)$ = EPR 'marking' matrix, where 1 represent eminent pixels.
$V_{LBP}(x,y)$ = Reconstructed concentration profile using LBP algorithm.
$V_{EPR}(x,y)$ = Improved concentration profile using EPR algorithm.

6.0 RESULTS AND DISCUSSION

To evaluate the sensitivity of the ultrasonic tomography system, an experimental model was built as illustrated in Figure 7. The experiment model consists of the experimental pipe (vertical column) which is filled with liquid (water) and a gas model. The setup in use simulates a typical measurement of the distribution pattern for the liquid-gas flow inside the vertical column.

Different static physical gas models with different diameter (Figure 8 - Figure 11) have been applied in order to simulate the presence of gas component in the investigated column. The smallest gas model used to test the sensitivity of the system during the experiment has a diameter of 2.5 mm.

By using ultrasonic sensors with a centre frequency of 333kHz, the ultrasonic tomography system were able to resolve the small test tube with a diameter of 2.5 mm (Figure 11) and the system was able to successfully reconstruct the images for small gas detection.

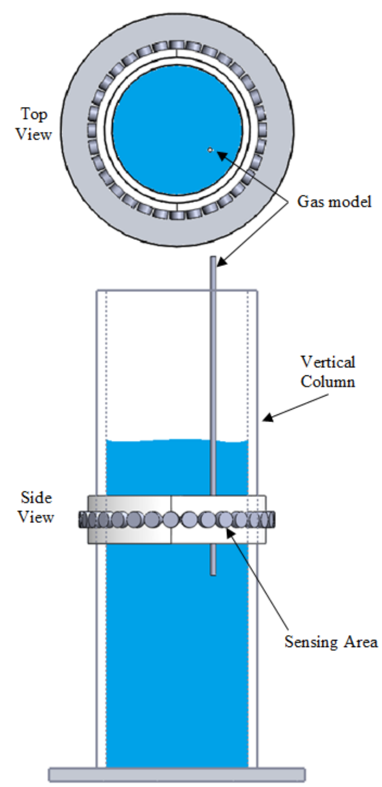


Figure 7 Experimental model

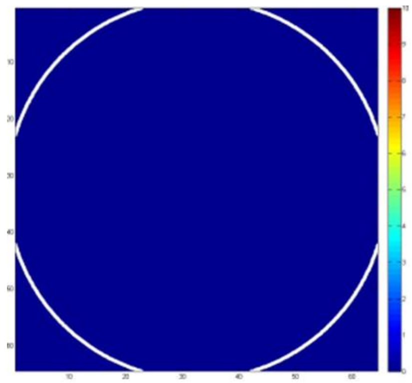


Figure 8 Vertical column is fully filled with liquid

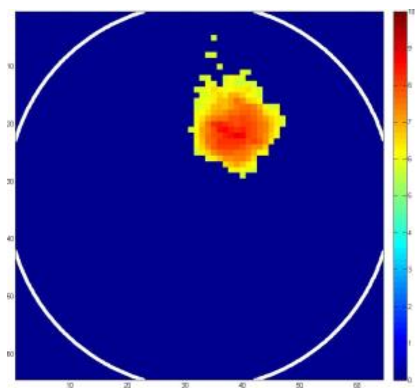


Figure 9 Gas model inserted with a diameter of 18.8 mm

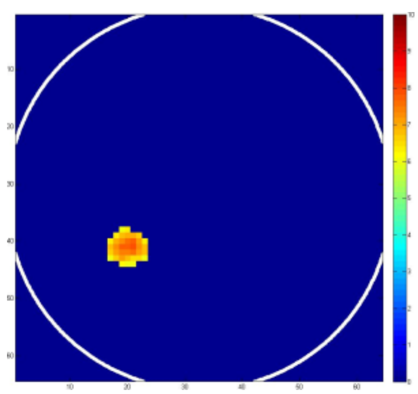


Figure 10 Gas model inserted with a diameter of 8 mm

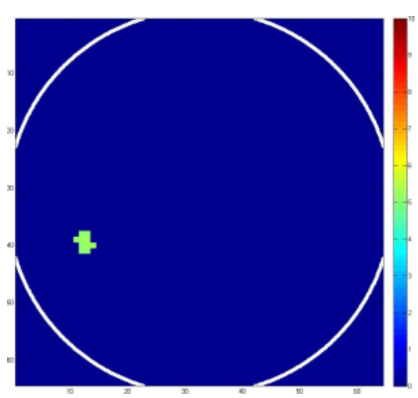


Figure 11 Gas model inserted with a diameter of 2.5 mm

■7.0 CONCLUSION

The non-invasive ultrasonic tomography for liquid/gas two-phase flow have been developed and investigated. The experimental results show that this system could be used to identify and detect small bubble in the investigated column. Ultrasonic sensors with much higher frequencies can be used if smaller detection of gas bubble is needed.

The limitation of ultrasound wave presents a trade-off challenge in developing an ultrasonic tomography system. The speed of ultrasound sets the upper limit of flow rates to which ultrasound techniques can be applied for flow imaging. To cater this natural disadvantage, it is vital that the flow activities inside the investigated column must be viewed from as many angles as possible, which can be solved by using fan-shaped beam projection.

The essence in utilizing the fan-shaped beam is that more information can be obtained from each interrogation. Transducers with such fan-shaped beam pattern will a cover a wide angle of the flow activities inside the column from a single excited transmitter.

Although it is apparent that a wide beam angle of ultrasound wave is important so that the system can gather information at a greater extent, the ultrasonic tomography system that employ wide-beam transducer will suffer in terms of attenuation of the ultrasonic beam with distance. Wide beam angles reduce the sensing range of the transducer by spreading acoustic energy over a greater volume and hence less acoustic energy is transmitted to the respective receivers.

When compared to wide beams, a transducer with narrow beam angles does not have the advantage of gaining more information in an individual interrogation but the ultrasonic tomography system that utilizes these sensors transmit more concentrated beam that travels over more distance with the added advantage of higher sensitivity.

Thus it is crucial to balance the trade-offs in developing an ultrasonic tomography system by considering the optimum frequency the system should use for the size of the column being investigated.

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