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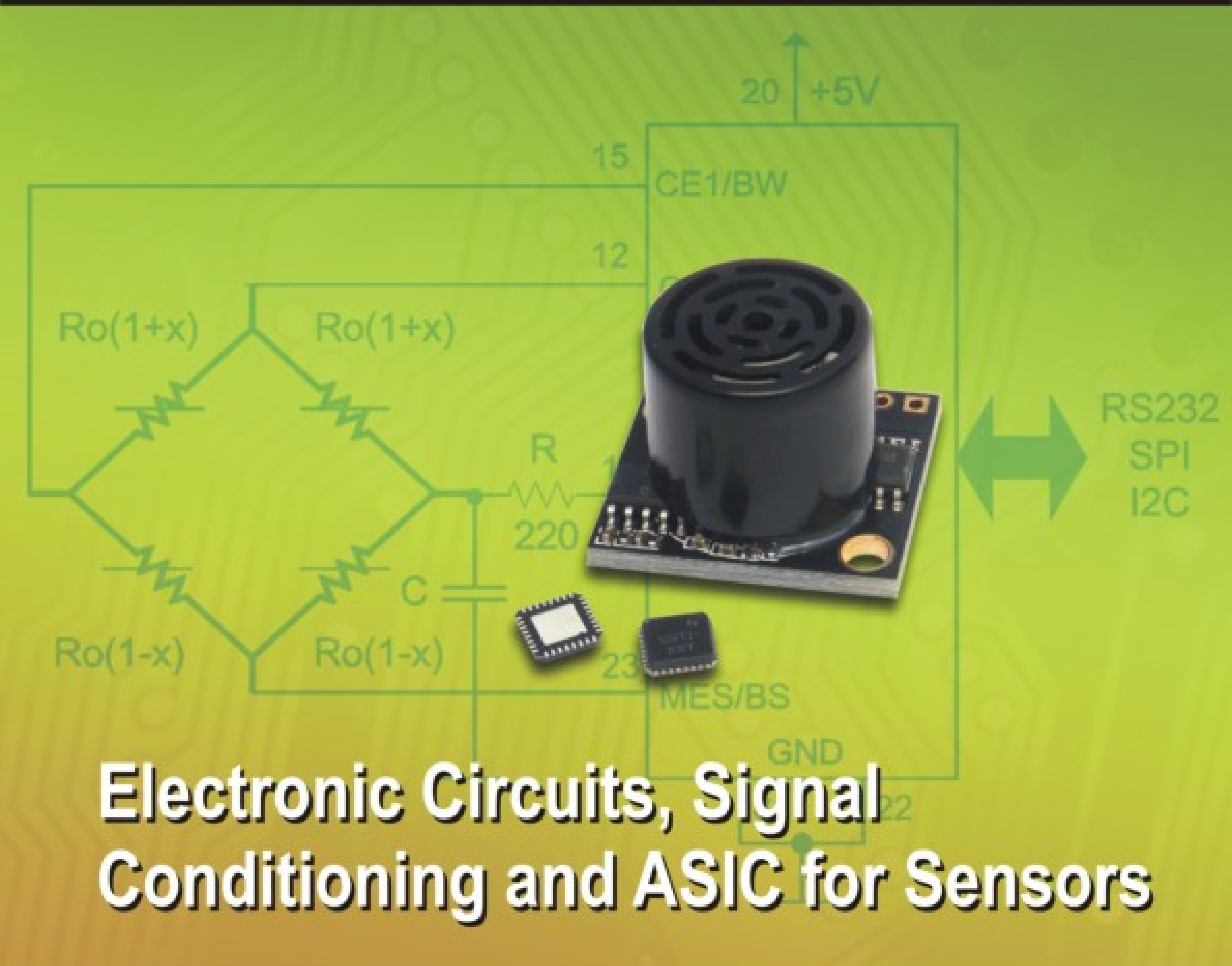

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The Hardware Design Technique for Ultrasonic Process Tomography System

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Abstract: This paper describes a work carried out to design and development an ultrasonic process tomography system. The hardware design technique is of interest of this paper. A number of 32-ultrasonic transducers have been employed and the interrogation of ultrasonic information is based on transmission-mode approach. The hardware design technique including the signal processing methodology and the data acquisition technique has been detailed. An embedded controller has been used on each channel to simplify the hardware design as well as for system synchronization. An auto-calibration approach has also been used to calibrate 544 signals information. At the end of the paper, several tomograms reconstructed using the sensor array is discussed. *Copyright © 2012 IFSA.*

Keywords: Ultrasonic Tomography, Embedded System, Ultrasonic Processing, Image Reconstruction

1. Introduction

Ultrasonic process tomography has been widely explored for imaging industrial two-phase flows especially in liquid/gas column. Ultrasonic method is favored because of it is possible to perform non-invasive measurement besides ultrasonic has well established as popular NDT tool. For instance, in biotechnology industries, improvement on the reactor performances for example in aerobic fermentation processes in order to optimize the oxygen released in the bioreactor is being researched. This is to ensure the growths of the microbes are optimum.

The goal of ultrasonic tomography is to reconstruct the spatial distribution of some acoustic parameter of an object using ultrasonic measurements [1]. In tomography process, the first step of tomographic process is to generate the integral measurements using a selected sensor. The second step is to reconstruct the property field (the cross-sectional distribution of the physical properties of the multiphase media) from the measured integral values. This process is called tomographic reconstruction [2].

The work reported in this paper demonstrates hardware design technique using 32-ultrasonic transducers working as transceivers for transmission-mode approach. The measurement technique is described first. Secondly, the hardware system consists of integrated embedded solution is described. Thirdly is the signal processing methodologies emphasizing on the hardware solution, fourthly, the data acquisition technique and fifthly is the image reconstruction process. Results on the reconstructed images using the systems are finally discussed.

2. The Measurement Technique

One of the challenges in ultrasonic process tomography is the ultrasonic speed. The ultrasonic speed is limited by the speed of sound i.e. in water the sound speed is 1500 m/s. It is important to achieve high processing speed in order to achieve real-time processing.

Generally, the spatial resolution of a system is depends on the number of the measurement section. The more measurement taken, the higher accuracy could achieve. The advantage of ultrasonic method is the capability to perform measurement in fan-shaped beam view. By insonify a transmitter, the receiver within the beam angle could pick-up the transmitted sound and the measurement can be based on the transmission, reflection or diffraction mode.

Our system consists of 32-transducers that were clamped-on a 100 mm diameter column with 333 kHz resonance. The transducer works on transceiver mode, that means capable of transmitting and receiving ultrasonic signal. We used a transmission-mode approach and for a single transmission there were 17 receivers responding to the measurement as shown in Fig. 1. A series of 32 views is required for one full scan on the column and resulting 544 measurements.

3. The Hardware System

The hardware block diagram is shown in Fig. 2. The hardware system was divided in two parts; one Master and 32 Slaves. The Master will control the overall operation of the system including selecting active transmitter. On the other hand, each transducer will be controlled by its dedicated slave controller unit. This approach makes the system independent and expendables for future use.

Each transducer was connected to an analog switch to control the direction of signal flows in and out during transmitting and receiving process. The analog switches were digitally controlled by the slave controller unit. The ultrasonic pulses from the slave controller unit were amplified by a MOSFET-based signal generator.

The signal conditioning circuit was used to reshape the receiving signal and the slave controller unit will trigger the sample and hold (S&H) and store the information in digital form in a buffer by a built-in high-speed analog-to-digital converter (ADC).

The Master controller unit then collects all data from the slave controller unit through high-speed SPI bus. The Master controller unit will compute for tomogram using image reconstruction algorithm and convey to PC via USB bus for displaying the results.

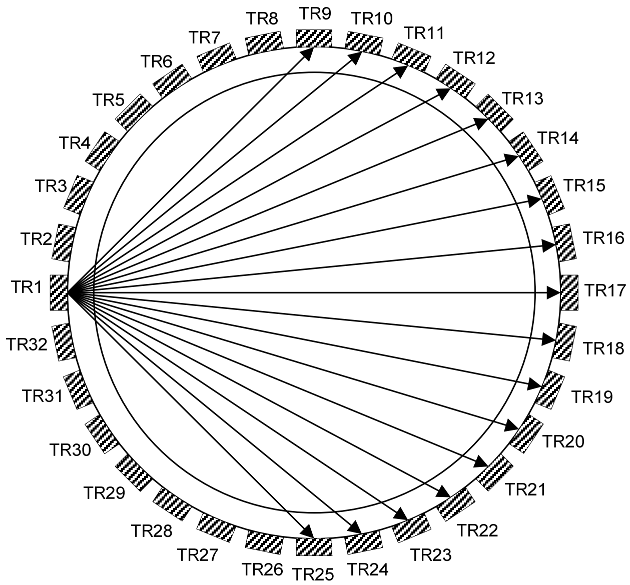


Fig. 1. A transmitter view on the receivers.

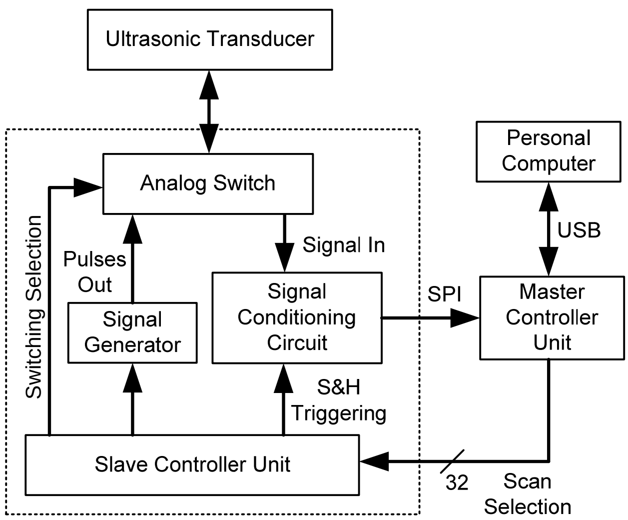


Fig. 2. The hardware block diagram.

4. The Signal Processing Methodology

The signal processing involves amplification, noise filtering and signal reshaping. The frequent problem in ultrasonic signal is noises. The noises sometimes affected badly on the ultrasonic signals and it is very hard to distinguish between the signal information and the noise. In flow measurement especially, the frequency of the noise due to mechanical vibrations of the pressure remains lower than 3 kHz, the noise due to turbulence and gas expansion is in ultrasonic range [3]. This is the problem we need to overcome beforehand. The signal conditioning circuit block function is shown in Fig. 3.

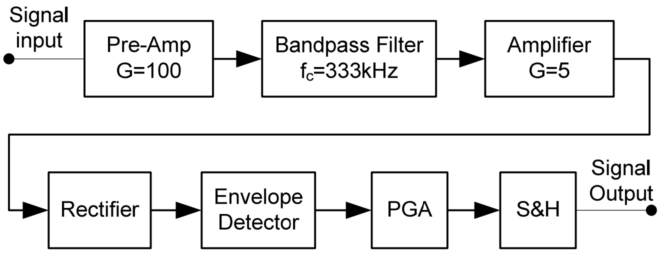


Fig. 3. Signal conditioning block function.

The weak receiver signal requires amplification. To avoid internal distortion due to gain-bandwidth (GBW) limitation of operational amplifier, the amplification was divided into two stages with gain, G=100 in the first stage, and G=10 in the second stage. The noise exhibits greater with clamped-on technique and the frequency spectrum of the receiver signal are shown in Fig. 4.

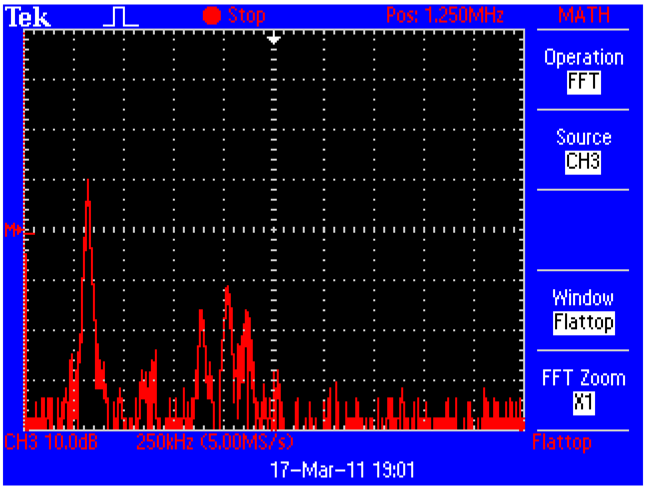


Fig. 4. The frequency spectrum of receiver signal after being amplified in the first stage.

The resonance frequency is 333 kHz. To preserve the frequency, noises from outside the frequency band must be omitted and this can be accomplished using a bandpass filter. For a narrow bandpass filter design, a Multiple Feedback topology was chosen and the cut of frequency, f_c was set equal to the resonance frequency. The frequency response of the bandpass filter and the frequency spectrum of the filtered signal are shown in Figs. 5 and 6 respectively. Fig. 7 shows the receiver response before and after filtering process. The filtered response is slightly attenuated and phase-shifted due to the nature of the bandpass filter. The attenuated amplitude is then amplified in the second stage.

Generally, for ultrasonic process tomography there are two ways of manipulating a transmission-mode ultrasonic receiver signal, by measuring the time-of-flight and the attenuation. The time-of-flight method is more suitable for investigation of homogenous media because it gives information on the boundary of two separated media like water and oil. The attenuation method on the other hand, is more superior for measuring two or more high-acoustic impedance mixtures [4]. Therefore, the attenuation method has been chosen in our design.

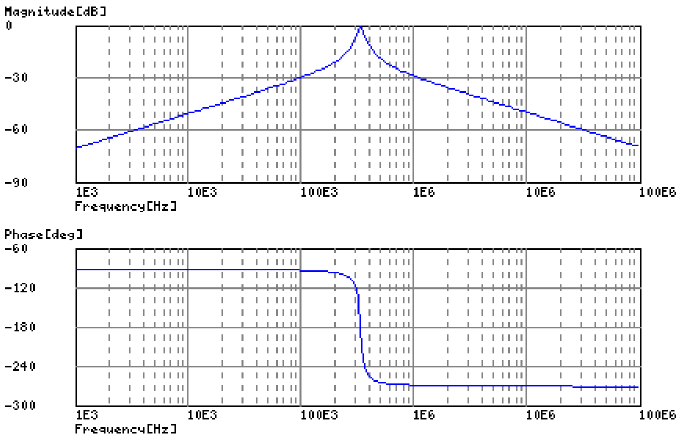


Fig. 5. The bandpass filter frequency response.

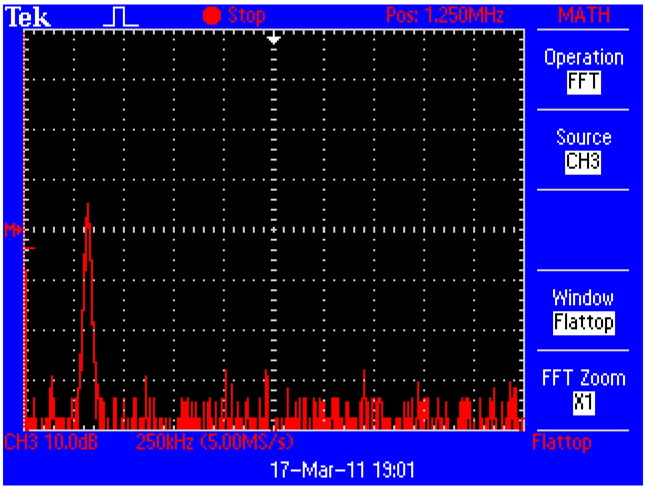


Fig. 6. The frequency spectrum of the filtered receiver signal.

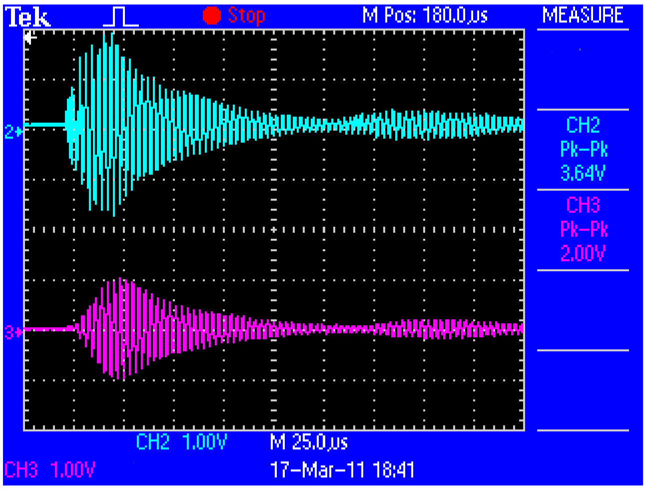


Fig. 7. The receiver signal response before (above) and after (below) filter.

The receiver response was converted in to DC level to ease the interfacing with embedded system. The DC level was obtained using a fast rectifier circuit or known as absolute value circuit resulting a full-wave rectification. For a clean DC response, an envelope detector was used for easier attenuation measurement. A programmable gain amplifier (PGA) provides a selectable gain for weak envelopes due to the different transducer positioning. The rectification and enveloping response are shown in Fig. 8. Finally, the amplitude is captured using the sample and hold (S&H) technique. The details regarding measuring the attenuation are discussed in the following section.

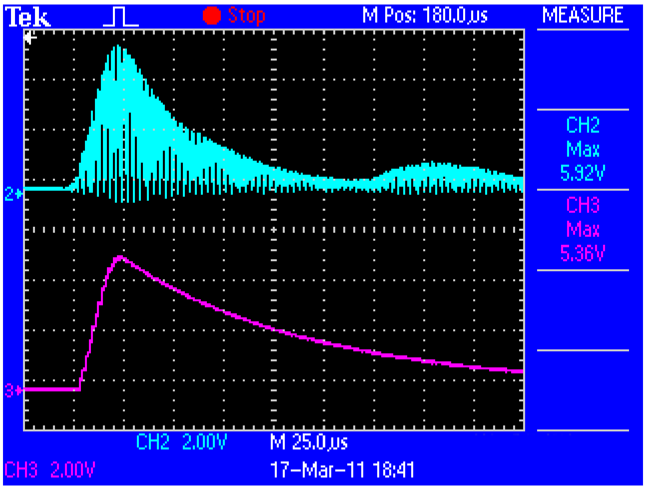


Fig. 8. The signal response after rectification (above) and enveloping process (below).

5. Data Acquisition Technique

One of the main hurdles in ultrasonic process tomography system is the time limitation. Each transmitted pulse takes around 66.67 μs (assuming speed of sound in water is 1500 m/s) to reach the opposite receiver for a 100 mm diameter column. Depends on the damping material used on the transducer, ringing & reverberation effects should fade away before the next transmission cycle begins. For a lightly damped transducer, a delay should be included between each transmission to allow residue vibrations fade away in the transducer.

In a liquid/gas column, one should clearly distinguish signal information at the receiver. Besides noise, reflected ultrasonic waves on the column wall and scattering phenomena in the column exhibit another major problem to researcher. To avoid misinterpretation of the signal information, one should capture the peak (amplitude) of the first time-of-transmission signal corresponding to a straight path and this point of time is known as the *observation time* [5]. This can be accomplished using a sample and hold technique. By pre-program the *observation time* in a microcontroller, the signal amplitude voltage could be obtained.

In our slave controller unit, we used an embedded system consists of a dedicated microcontroller to accommodate an independent system for precision timing, high-speed analog-to-digital conversion (ADC) running at 1 Mbps, system synchronization and high-speed interfacing. To log a series of 544 independent *observation time* for each measurement requires a lot of effort. For simplicity, we have created an auto-calibration system that will log all the *observation times*. The auto-calibration system was programmed onto the slave controller unit to automatically search for the first highest amplitude and store the *observation time* in the buffer. Hence, each slave controller unit will search for the *observation time* for all 32 transmitter projections. The auto-calibration procedure is discussed in the following.

The built-in timer has a 32-bit resolution, thus ensures accurate timing computation. When a transmission occurred, the timer starts its clock. The high-speed ADC performs continuous signal sampling. For each sampled data, $V(t_n)$ will be compared with the previous data $V(t_{n-1})$ in order to obtain the first highest amplitude and when the point is found, the ADC and timer stop and store the point of time in the buffer. The procedure is shown in Fig. 9.

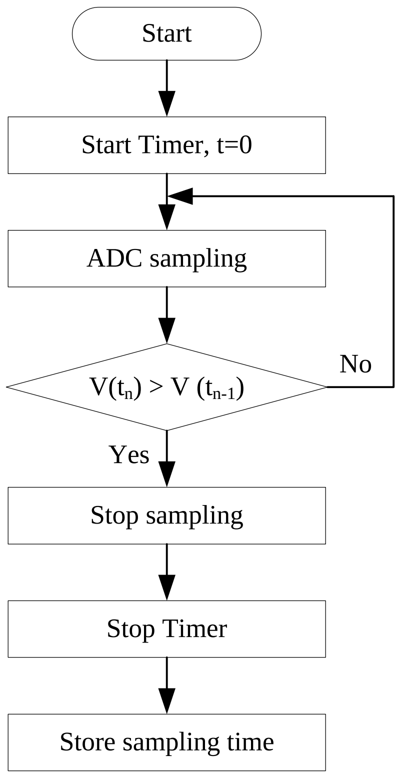


Fig. 9. The procedure for searching the *observation time* in the receiver signal.

This procedure will be executed during calibration stage that is, before performing any measurement with the column filled with liquid only. During each measurement, the slave controllers will capture the signal amplitude corresponds to the pre-program timing and compute the attenuation using equation 1:

$$V_G = V_C - V_R, \tag{1}$$

where V_G is the attenuation voltage, V_C is the calibration voltage and V_R is the receiving voltage.

The attenuation voltage is stored in the slave controller buffers collectively until completion of 32 transmissions and transmitted to Master controller through high-speed SPI bus. The Master controller holds responsibility to compute the image reconstruction algorithm and transfer the result to PC via USB link for tomogram generation.

6. Image Reconstruction Process

Generally, there are two types of reconstruction algorithm approaches; the analytical method and the iterative method. The popular analytical method is Back-Projection technique which is widely acceptable and has been used in most medical tomography scanner whereas; the Algebraic Reconstruction Technique (ART) is a popular iterative method which involves several iteration processes to obtain the tomograms [6].

The choice of the reconstruction algorithm is however dependent on the sensor system selected. In engineering applications, the number of measurement is usually small compared to medical applications to perform a real-time measurement or limited by constraints on the sensor employed. Therefore, the reconstruction results are then further corrected using a mathematical approximation to obtain a better reconstruction [7].

In Linear Back Projection algorithm (LBP), the concentration profile is generated by combining the projection data from each sensor with its computed sensitivity maps [6]. The modeled sensitivity matrices are used to represent the image plane for each view. To reconstruct the image, each sensitivity matrix is multiplied by its corresponding sensor loss value; this is same as back project each sensor loss value to the image plane individually. Then, the same elements in these matrices are summed to provide the back projected voltage distributions (concentration profile) and finally these voltage distributions will be represented by the color level (colored pixels) [8]. This process can be expressed mathematically in equation 2:

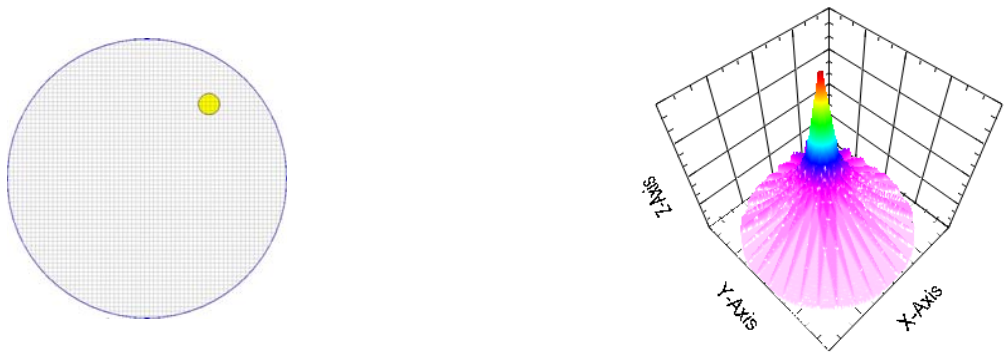
$$V_{LBP}(x, y) = \sum_{Tx=1}^{m} \sum_{Rx=1}^{n} S_{Tx,\,Rx} \times \overline{M}_{Tx,\,Rx}(x, y) \quad (2)$$

where V_{LBP} (x, y) = the voltage distribution obtained using LBP algorithm in the concentration profile matrix, $S_{Tx,Rx}$ = the attenuation voltage for the corresponding transmission (Tx) and reception (Rx) and $\overline{M}_{Tx,\,Rx}(x, y)$ = sensitivity matrices.

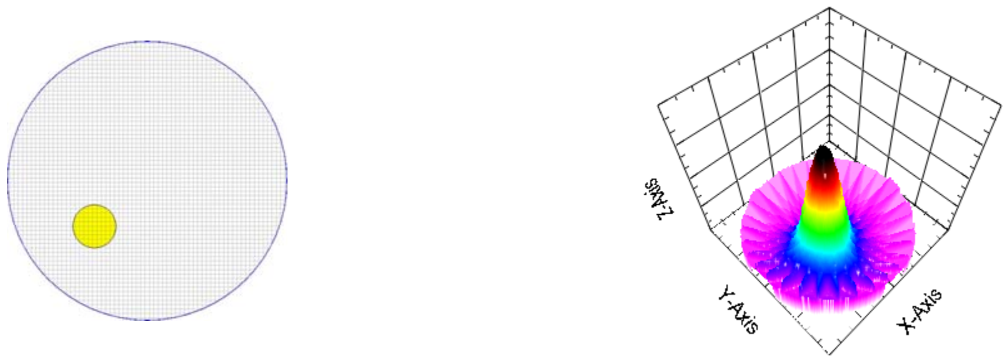
Fig. 10 shows the reconstructed tomogram of several gas bubble hold-ups in liquid column using 32-sensor array based on arrangement in Fig. 1. A significant advantage of a fan-shaped beam is, the measurement can be obtained from many angles, and thus provides more detail information on the imaging area. Fig. 10 (a) and (b) show a single gas hold-up at different location with gas hold-up in (b) larger than in (a). When the number of gas hold-ups increased to two and three as shown in Fig. 10 (c) and (d) respectively, the images clearly indentified the location and size of the hold-ups.

6. Conclusions

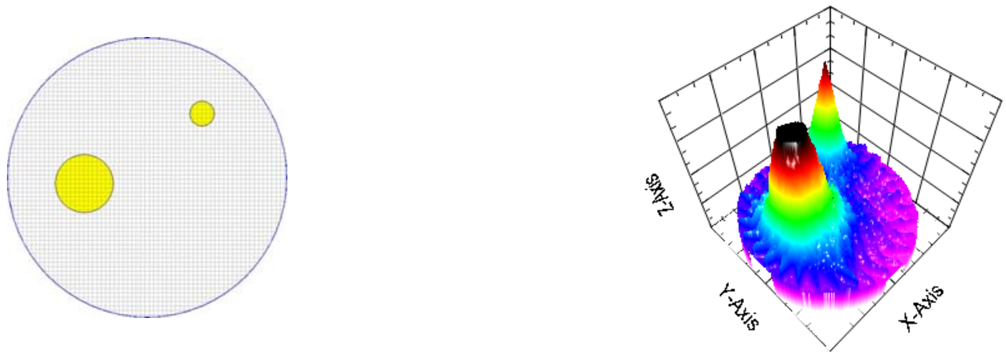
The hardware design technique for ultrasonic process tomography system has been discussed. To manage a series of 32 sensors using independent embedded controller is highly recommended. This enables a manageable system when interfaced for synchronization. Besides, the transmissions and receptions can be digitally controlled for a more robust and sustainable system. On the other hand, the embedded controller allows an auto-calibration system to be in place. Based-on the sensor array, a number of 544 measurements are made in one full scan resulting higher spatial resolution. This is obvious when imaging more gas hold-ups in a liquid column.



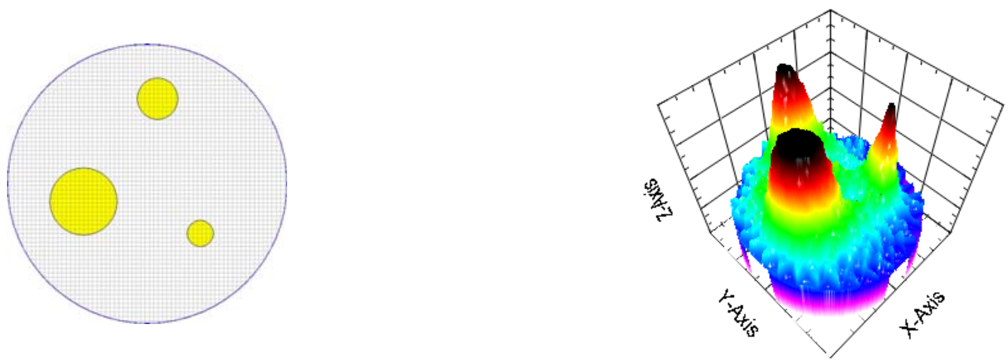
(a) Single gas hold-up (small)



(b) Single gas hold-up (large)



(c) Dual gas hold-ups



(d) Triple gas hold-ups

Fig. 10. Gas hold-ups images using fan-shaped beam projections.

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Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

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- Virtual instruments;
- Sensors interfaces, buses and networks;
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- Applications.

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