ISSN 1726-5479

# SENSORS & TRANSDUCERS

1 /10 vol. 112


## Sensor Instrumentation, DAQ and Virtual Instruments

International Frequency Sensor Association Publishing

IFSA

# Sensors & Transducers

Volume 112, Issue 1
January 2010

www.sensorsportal.com

ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD. 

Sensors & Transducers Journal

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Volume 112
Issue 1
January 2010

www.sensorsportal.com

ISSN 1726-5479

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International Frequency Sensor Association (IFSA).

*Sensors & Transducers Journal, Vol. 112, Issue 1, January 2010, pp. 24-38*

**Sensors & Transducers**

**ISSN 1726-5479**

*http://www.sensorsportal.com*

# Simulation of the Two-Phase Liquid – Gas Flow through Ultrasonic Transceivers Application in Ultrasonic Tomography

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*Received: 28 October 2010 /Accepted: 22 January 2010 /Published: 29 January 2010*

**Abstract:** In this paper, ultrasonic transmission mode tomography was used to visualize the two phase liquid/gas flow in a pipe/vessel. The sensing element consists of 8, 16 and 32 units ultrasonic transceivers were used to cover the pipe cross-section at different time. The motivation of this paper is to analyze the optimum numbers of transceivers which can give the best performance in providing better image of the two phase liquid/gas flow. This paper also details the development of the system including the ultrasonic transduction circuits, the electronic measurement circuits, the data acquisition system and the image reconstruction techniques. Ten conditions of liquid-gas flow have been simulated. The system was found capable of visualizing the internal characteristics and provides the concentration profile for the corresponding liquid and gas phases while the 32 transceivers has provided the best image for the ten conditions applied. *Copyright © 2010 IFSA.*

**Keywords:** Ultrasonic tomography, Ultrasonic transceivers, Liquid and gas flow, Flow measurement system

## 1. Introduction

Real time process monitoring plays a dominant role in many areas of industry and scientific research [3, 12] since there is a widespread need for the direct analysis of the internal characteristics of process plants in order to improve the design and operation of equipment. The measuring instruments for such applications must use robust non-invasive sensors which, if required, can operate in aggressive and fast moving fluids and multiphase mixtures. A good tomography sensor should have the features such as non-invasive and non-intrusive. It should not necessitate rupture of the walls of the pipeline and do not disturb the nature of the process being examined [10]. Process Tomography involves the use of instruments which provide cross sectional profile of the distribution of materials in a process vessel or pipeline [8] and can be used to obtain both qualitative and quantitative data needed in modeling a multi flow system [6]. A basic tomography system is constructed by the combination of sensor system, data acquisition system, image reconstruction system and display unit while the sensor system is the heart of any tomography system [10]. In the other hand, the transducers configuration is a key factor in the efficiency of data acquisition [6]. The number of transducers that can be used is functionally limited by the real time scheme, which in turns relies upon the available computing power and the physical dimension of the imaging cross section [9].

## 2. Ultrasonic Tomography

Ultrasonic tomography technique is the use of ultrasound to detect the changes of acoustic impedance ($Z$) which is closely related to density ($\rho$) of the media ($Z = \rho c$ , where $c$ is the velocity of the sound) [1-3, 7] and thus complements other imaging technologies such as Electrical Capacitance Tomography (ECT) and Electrical Impedance Tomography (EIT) [3, 7]. An ultrasonic tomography system is based upon interaction between the incident ultrasonic waves (frequency of 20 kHz to 10 MHz) and the object to be imaged [1]. Whenever there is an interface between one substance and another, the ultrasonic wave is strongly reflected [2] and this type of tomography technique has the advantage of imaging two components flow and gives the opportunity of providing the quantitative and real time data on chemical media within a full scale industrial process [3]. However ultrasound has several specific problems which may limit its application. The speed of sound in gas limits the data acquisition rate and particle impact on the flow pipe may produce very high levels of noise at the transducer [8].

## 3. Ultrasonic Sensing Modes

There are three modes of the ultrasonic tomography systems, the transmission mode, reflection mode and diffraction mode [1]. 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 medium. Transmission mode tomography is used when in the case of forward scattering, if the data acquired only concern the amplitude and/or time of flight and a reconstruction algorithm is based on the assumption of straight line propagation is applied. There are two major constraints in on the application of the transmission mode ultrasonic techniques that are limitation by media absorption and the limitation by complex sound field [2, 7]. The reflection mode technique is based on the measurement of the position and the change of the physical properties of wave or a particle reflected on an interface, while diffraction mode technique is based on diffraction or refraction of wave at a discrete or continuous interface in the object space. Ultrasonic tomography poses a problem where the real time performance is paramount: the complex sound field sensed by transducers often resulting in overlapped, or multiple reflected pulses which introduce errors; and the inherent slow propagation speed of ultrasound lowering the scanning speed. In order to eliminate these problems spectral analysis strategy is applied, which examined the phase information of reflected ultrasonic signals detected by a transducer [4, 5]. The behaviour of a normal ultrasonic wave front at interfaces in terms of power reflection ($P_r$) and power transmission ($P_T$) coefficient are given by the formula:

$$P_r = \left(\frac{p_r}{p_i}\right)^2 = \left[\frac{(Z_2 - Z_1)}{(Z_2 + Z_1)}\right]^2, \quad (1)$$

where $P_r$ is reflected sound pressures, $P_t$ is transmitted sound pressures, and $P_i$ is incident sound pressures. It is obvious in equation (1) that if the difference of the acoustic impedance between the two medium at an interface is greater, thus the reflected energy is also greater. If most of the energy is reflected so very less of it is received. This is the situation at the sensor and pipe interface. To overcome this problem, an acoustic coupling is introduced between the sensor's surface and the outer pipe wall. The function of this coupling is to match the acoustic impedances between two different mediums (by providing a free air region between the sensor's surface and the pipe wall) and will produce an optimum transference of the acoustic energy from the transmitter to the receiver [2, 3].

## 4. Transceiver Sensing Method & Setup

Dual functional gives transceivers advantages since less number of sensors are enough to generate same quality of image compare to separate transmitter-receiver. Each time, transceiver can only be a transmitter or a receiver and cannot both. When a transceiver is set to be a transmitter, it then switched to a transmitter circuit and at the same time off from the receiver circuit. The same thing happen when it is set to be a receiver, it then be switched to a receiver circuit and at the same time off from the transmitter circuit. The timing for the switching is very important since wrong switching timing will give inaccurate measurement data. In this research quad analogue switch is used for the switching process. The cross sectional area of the process vessel (acrylic pipe is used in this experiment) is shown in Fig. 1 (a) with 16 transceivers, noted as TR1-TR16 and located in a sensor jig in Fig. 2.

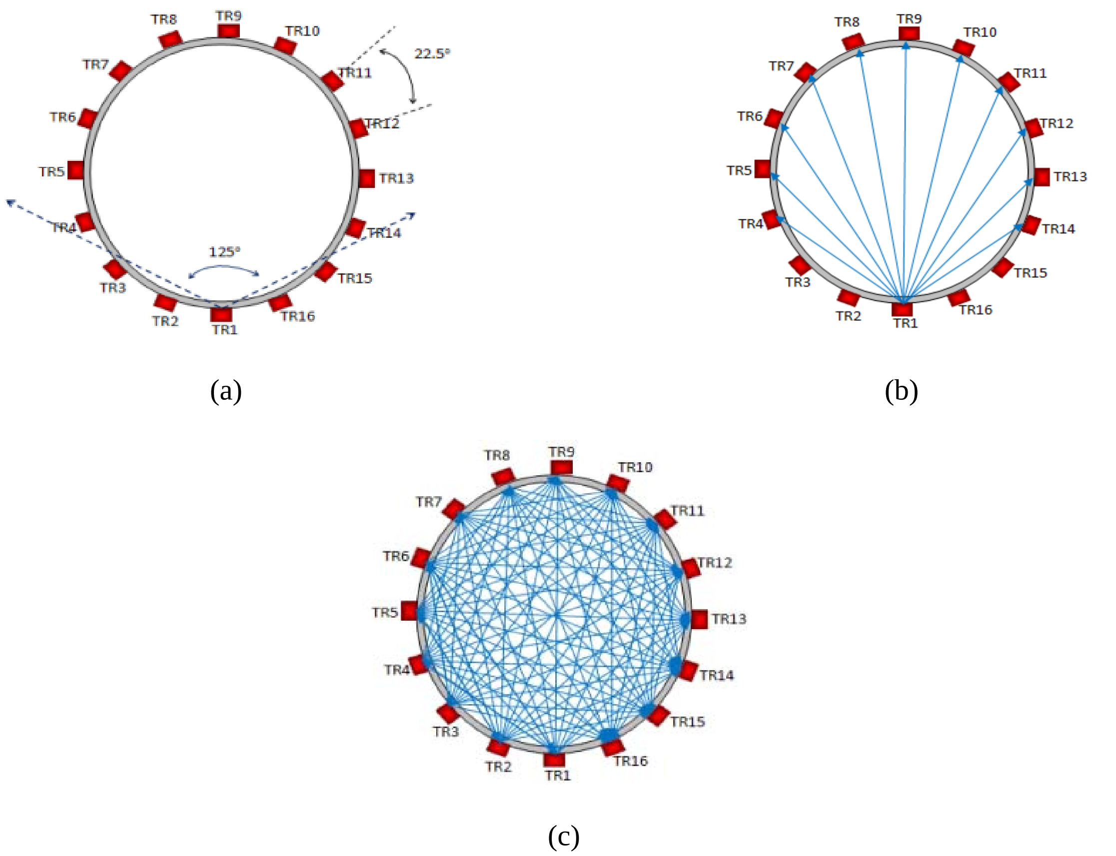


**Fig. 1.** (a) Cross section of process vessel; (b) Single scanning geometry; (c) Sixteen scanning geometry.

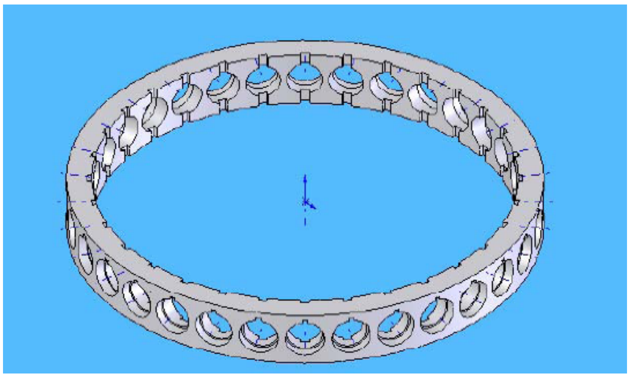

**Fig. 2.** Sensor jig.

Each transceiver has 125° beam angle. From the figure it is clearly shown that only 11 transceivers are located within this 125° beam angle at each projection. That mean only these 11 transceivers will received the projected signal. The rest 4 outsides the beam angle will not be considered in the measurement due to Lamb wave propagation. From there it is clear that for one full scan a total of 16 observations are made with 11 received channels each, hence 176 independent measurements were obtained.

## 5. The Electronic Measurement Circuit

Getting accurate data is the essence and vital in any tomography technique since through these data image is reconstructed. In ultrasonic tomography system, the basic preparations of measurement system are the hardware part, interfacing and also computer part as shown in Fig. 3. In the hardware part there are signal generator and signal conditioning circuit. Microcontroller (PIC18F452) unit is used as signal generator to generate and control the projection of 40 kHz signals (the frequency depends on the types of sensors used) to transmitters while the receiver will received the projected signal [2, 3]. The projected signal is shown in Fig. 4. Since transceivers are dual functional transducers (transmitter and receiver), analogue switches are used in the switching circuit to switch the transceiver to transmitter circuit or receiver circuit. In the signal conditioning circuit, the received signal is filtered using suitable filter to reduce the noise effects and then amplified through some amplifier circuits. A received signal which has been directly transmitted (no obstacle) can therefore distinguish from a reflected signal (due to obstacle), which must have a longer delay time.

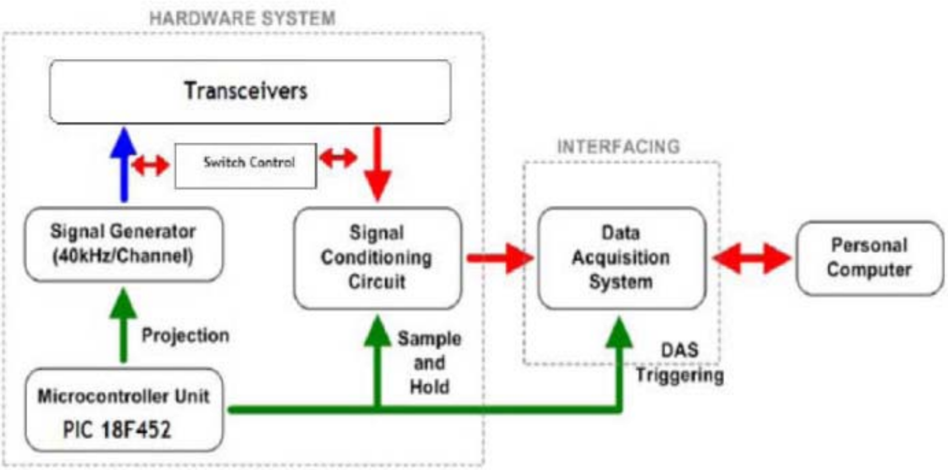


**Fig. 3.** Ultrasonic tomography system.

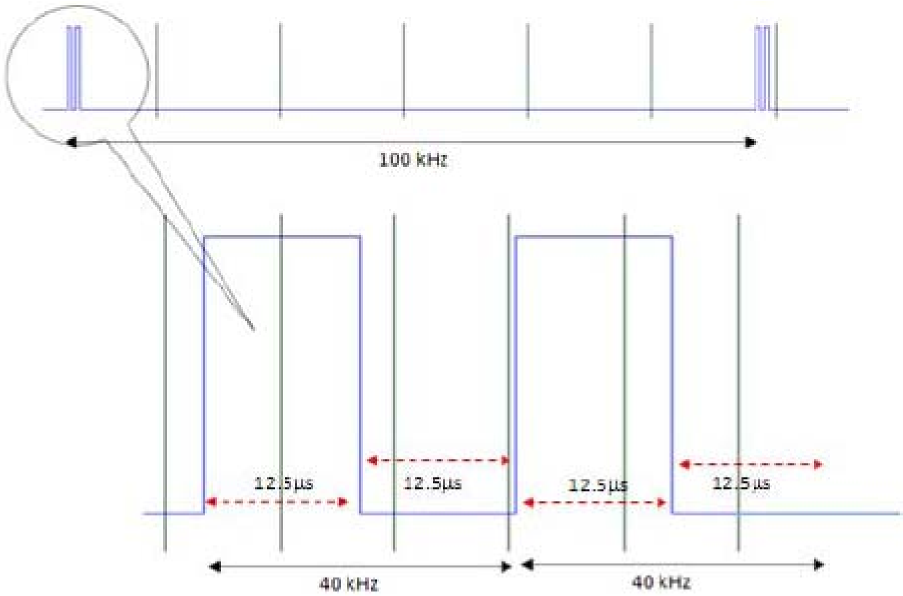


**Fig. 4.** Projected signal for a channel.

A sample and hold technique is used to capture (sample) and hold the analogue voltage in a specific point in time ($t_s$) under control of an external circuit (microcontroller) as in Fig. 5. By using the data acquisition system, the sampled signals are acquired into the computer and at the same time, a suitable image reconstruction algorithm can be used for visualizing the internal characteristics of the corresponding process vessel [2].

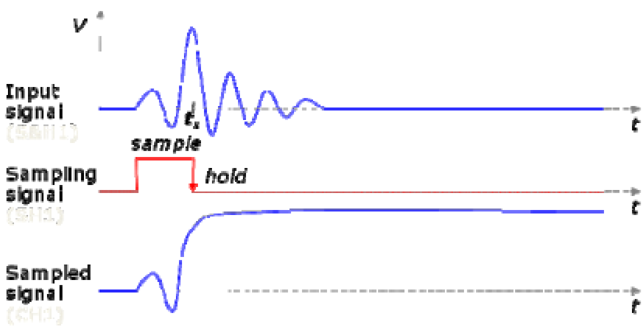


**Fig. 5.** Sample and hold technique.

## 6. Image Reconstruction Algorithm

After measurements have been done, the collected data will then be converted to the image through a suitable image reconstruction algorithm. If the scanning of each tomogram slice is fast and a set of axially spaced slice views is obtained, they can be assembled into a whole body image as shown in Fig. 6. There are many types of algorithm that can be used depends on the techniques that have been applied. They can be divided into two groups which are non iterative and iterative methods. The resolution of tomographic images that are reconstructed from measurements depends on the number of sensors arranged around the flow as well as the spatial resolution of each sensor array [13]. Artifacts and noise become more pronounced as the number of transducer positions is reduced [9].

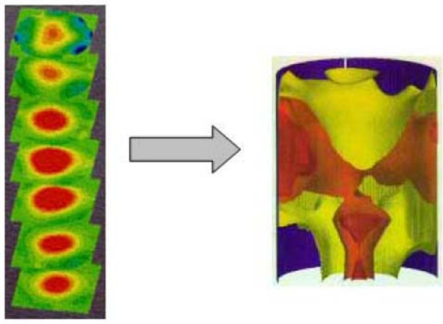

**Fig. 6.** Image reconstruction concept.

Most of the work in process tomography has focused on the use of Linear Back Projection (LBP) algorithm. The LBP is computationally straight forward to implement besides low computation cost and is popular method for image reconstruction [3]. The measurements obtained at each projected data are the attenuated sensor values due to object space in the image plane. These sensor values are then back projected by multiply with the corresponding normalized sensitivity maps by using the formula:

$$V_{LBP}(x,y) = \sum_{Tx=1}^{16}\sum_{Rx=1}^{16} S_{Tx,\,Rx} \times \overline{M}_{Tx,\,Rx}(x,y)\,, \tag{2}$$

where $V_{LBP}(x, y)$ = voltage distribution obtained using LBP, $S_{Tx,Rx}$ = sensor loss voltage of transmitter ($T_x$) and receiver ($R_x$) and $\overline{M}_{Tx,Rx}(x,y)$ = Normalized sensitivity maps.

The back projected data values are smeared back across the unknown density function (image) and overlapped to each other to increase the projection data density. The smearing effects is the side effect of the LBP since each pixels are summations of the back projected signals. Therefore, in this case, the 'wrong' pixels are summed twice by the value of the smearing effect. This produces ambiguous image since the reconstructed image may represent two, three or four pixels [11].

## 8. Results

The investigations were based on the transmission and the reception of the ultrasonic transceivers that were mounted circularly on the surface of the test pipe (acrylic pipe). The experiment were carried out on the test pipe to simulate the flow of liquid (water) and gas (air) with ten static conditions as shown in Fig. 7 to Fig. 11 that are annular flow, quarter flow, half flow, three quarter flow, single gas bubble, and dual gas. For experimental purposes, the flows for these seven conditions were assumed static. This assumption is to ease the experiment and analysis of the two phase liquid/gas flow.

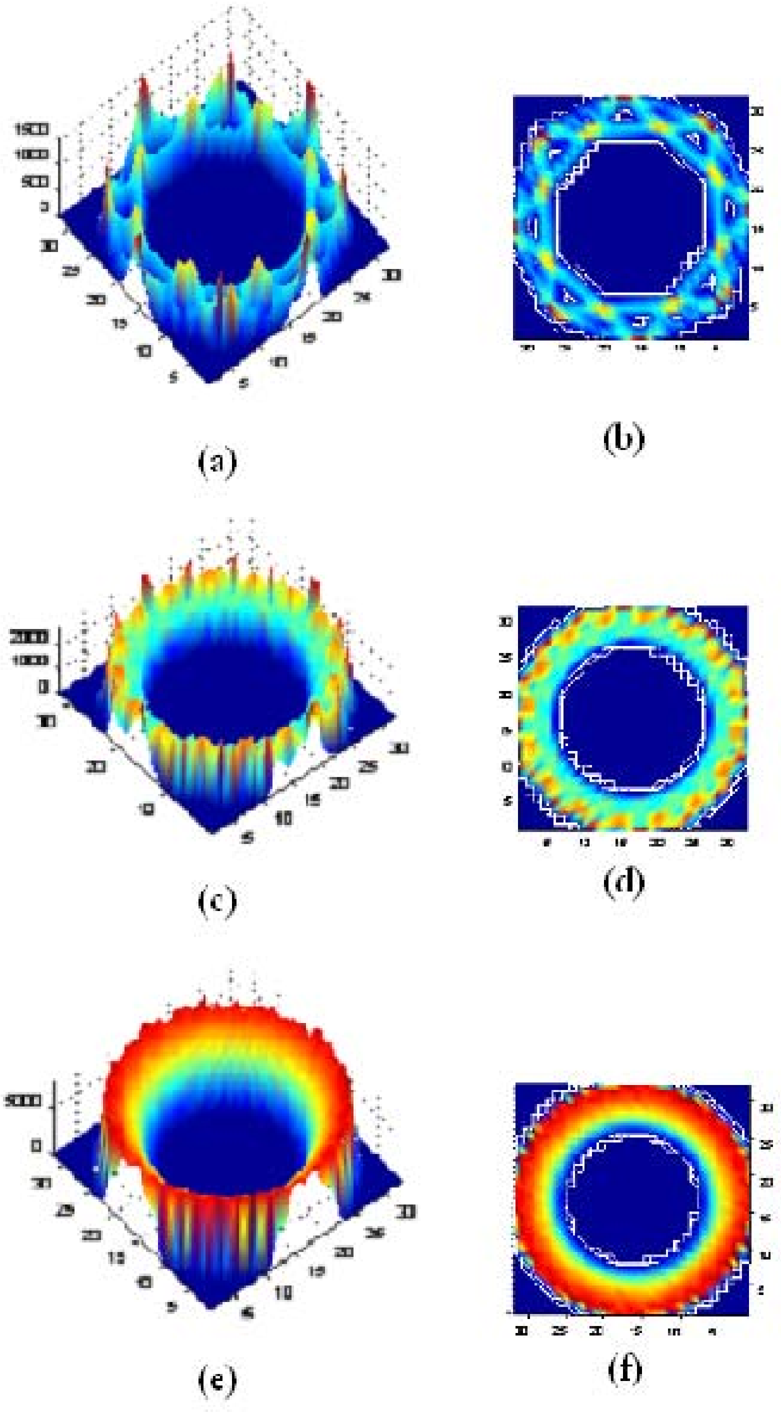


**Fig. 7.** Simulation result of annular flow for (a) and (b) eight transceivers; (c) and (d) sixteen transceivers; (e) and (f) 32 transceivers.

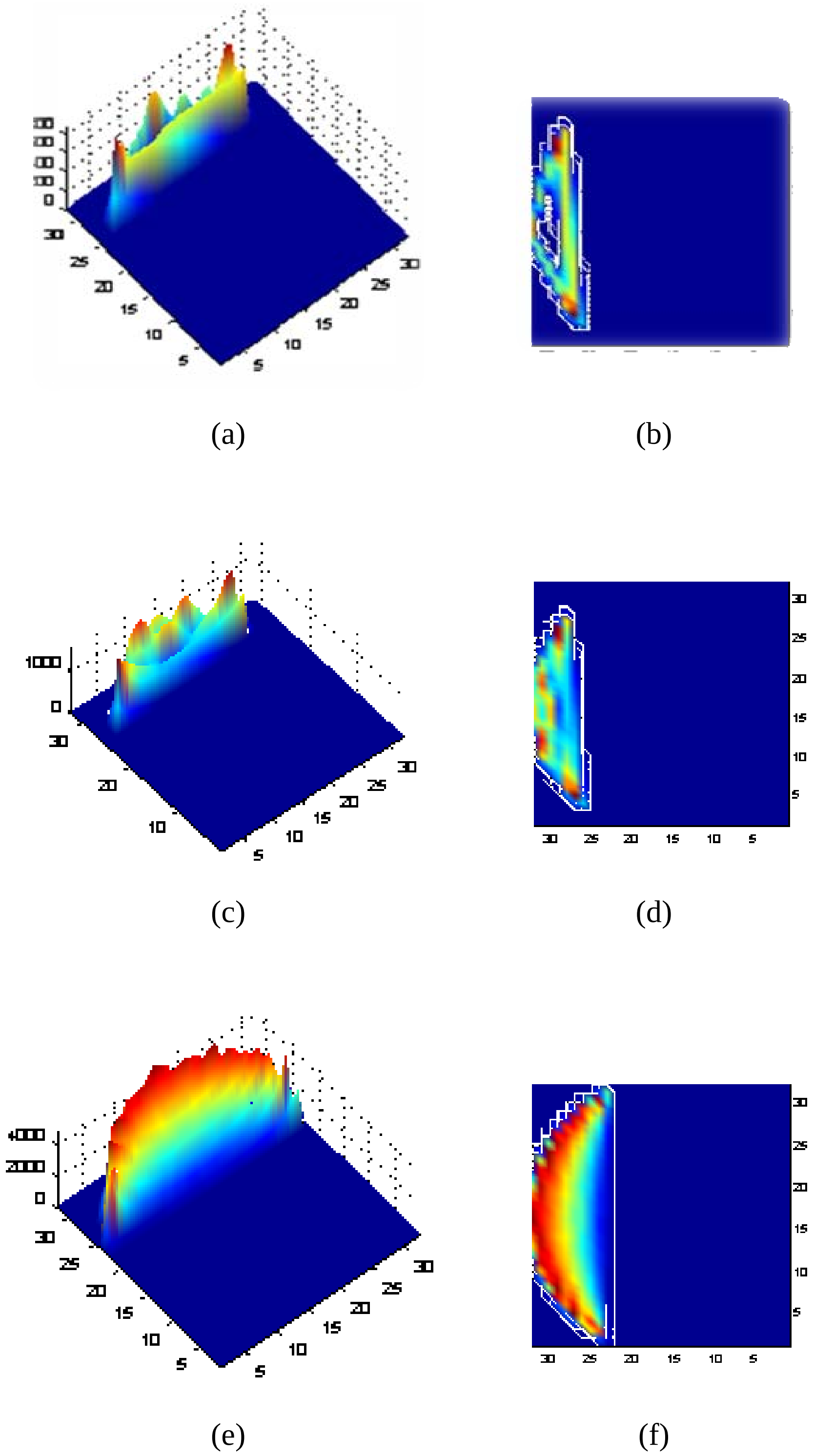

**Fig. 8.** Simulation result of quarter flow for (a) and (b) eight transceivers; (c) and (d) sixteen transceivers; (e) and (f) 32 transceivers.

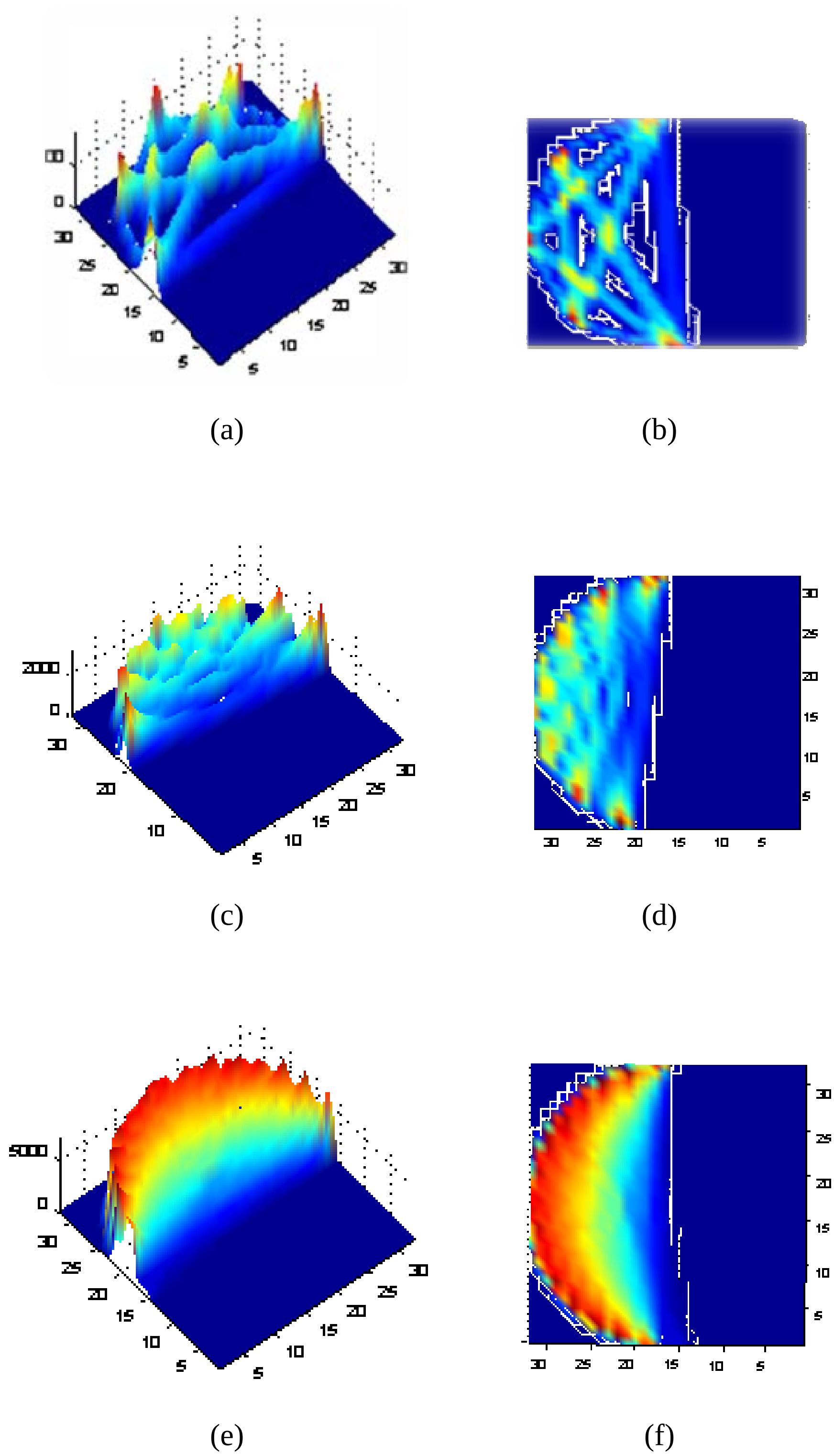


**Fig. 9.** Simulation result of half flow for (a) and (b) eight transceivers; (c) and (d) sixteen transceivers; (e) and (f) 32 transceivers.

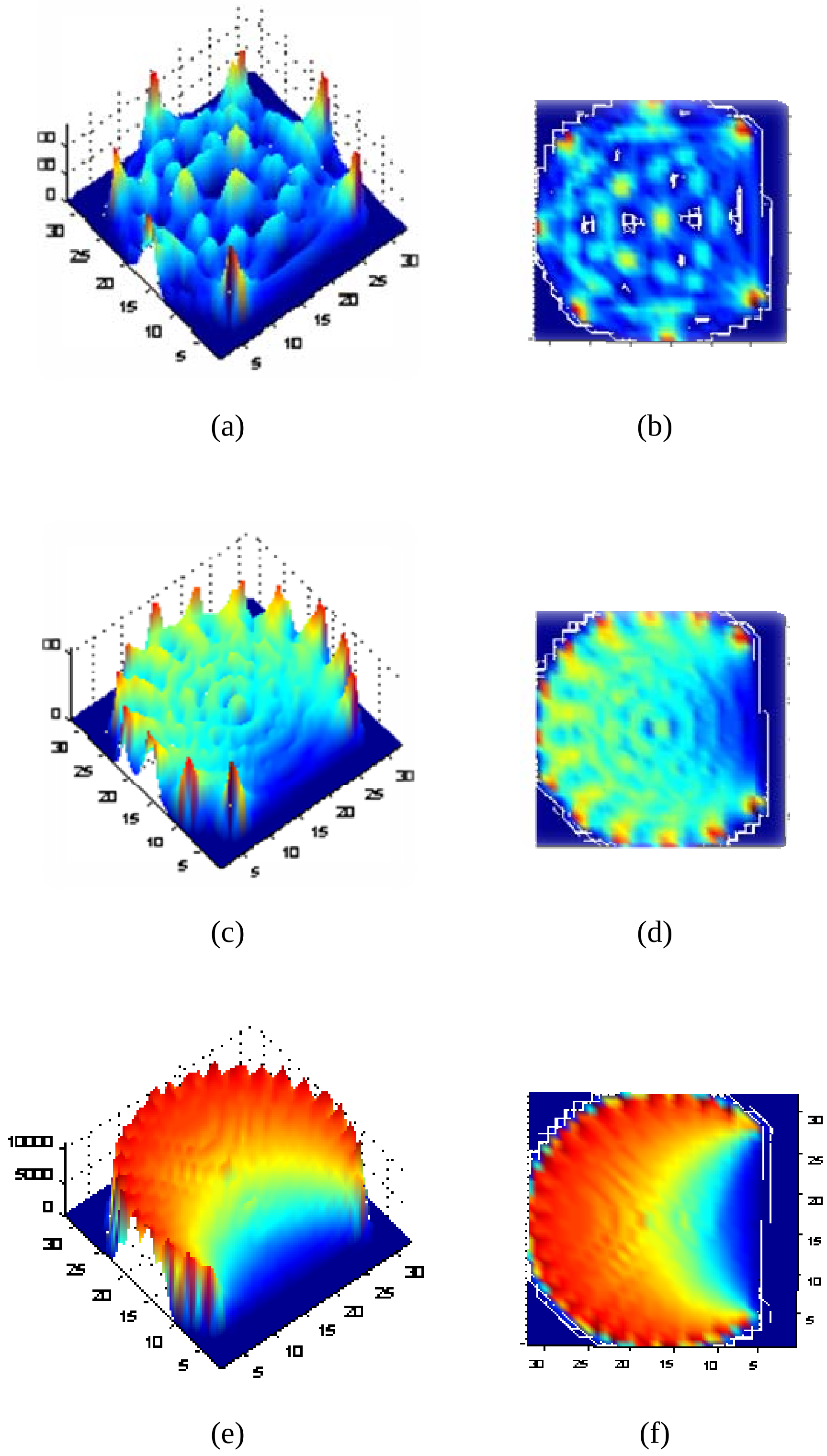


**Fig. 10.** Simulation result of three quarter flow for (a) and (b) eight transceivers; (c) and (d) sixteen transceivers; (e) and (f) 32 transceivers.

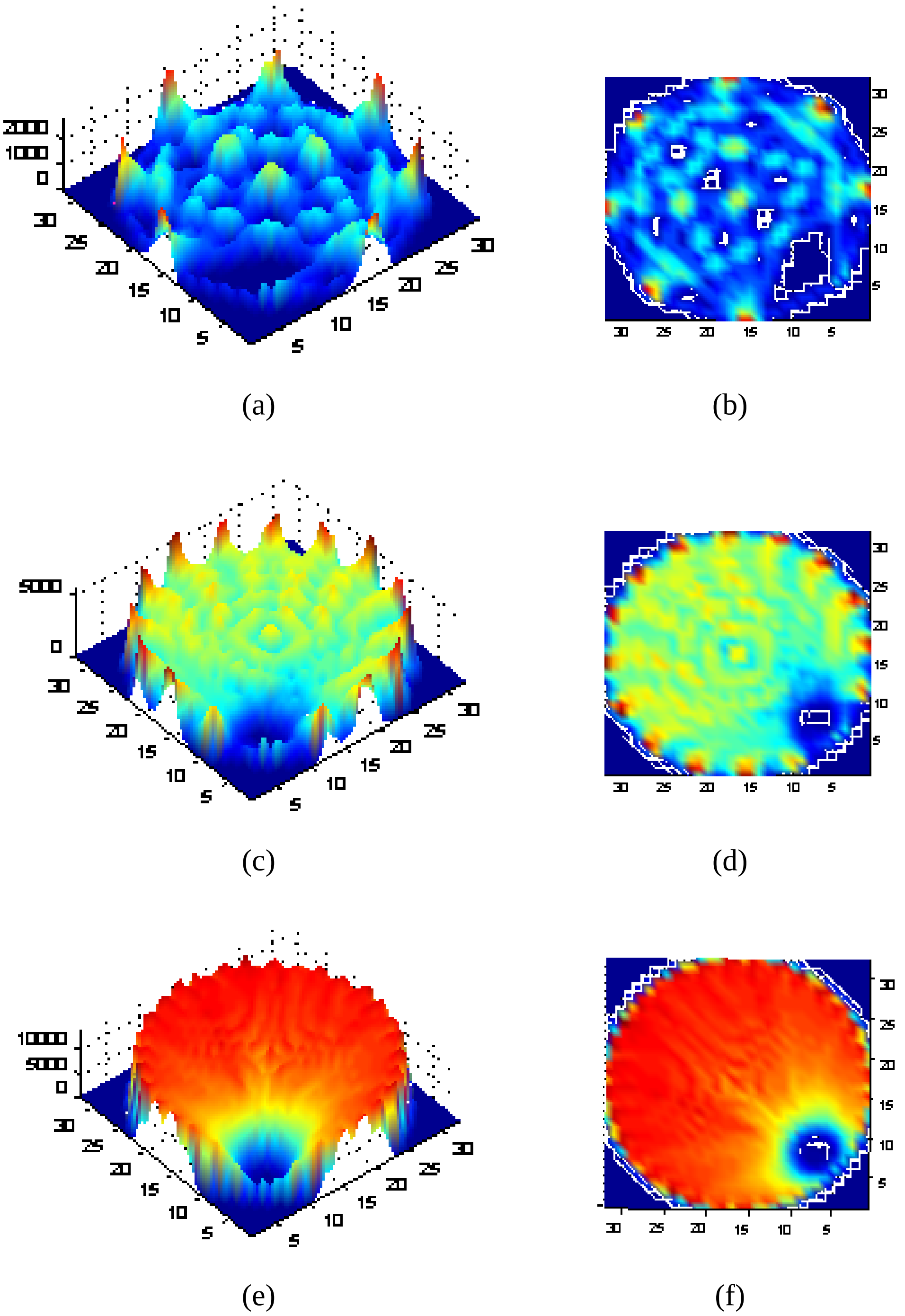


**Fig. 11.** Simulation result of single gas bubble for (a) and (b) eight transceivers; (c) and (d) sixteen transceivers; (e) and (f) 32 transceivers.

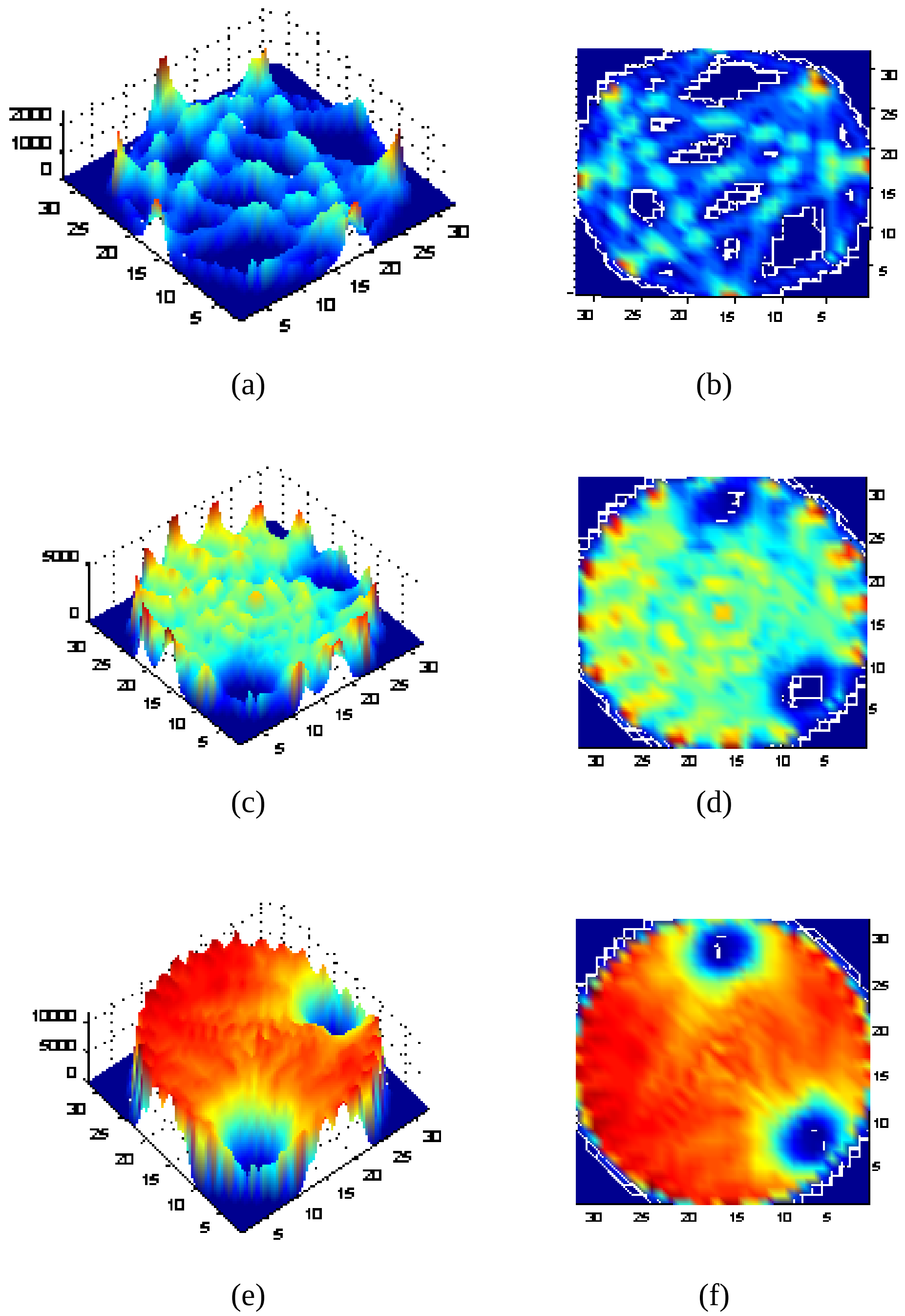


**Fig. 12.** Simulation result of dual gas bubble for (a) and (b) eight transceivers; (c) and (d) sixteen transceivers; (e) and (f) 32 transceivers.

## 9. Evaluation of Transceivers Performance

*Area Error, AE* as shown in Fig. 12 is used for *quanti*fying the quality of the reconstructed images in this system. All the *AE* values have the negative sign (-) and this tell us that all the reconstructed images are smaller in size compare to standard model (actual size). The evaluation of transceivers performance is based on the percentage of area error, *AE* which is given by the formula:

$$AE = \frac{\sum_{j=1}^{M} G_s(p) - \sum_{j=1}^{M} G_g(p)}{\sum_{j=1}^{M} G_s(p)} = \frac{N_R - N_S}{N_S} = \frac{N_R}{N_S} - 1 \,, \tag{3}$$

where $G_s(p)$ is the standard (test) model pixels, $G_g(p)$ is the binary reconstructed image pixels, $N_R$ is the number of pixels with non-zero colour levels in the reconstructed images and $N_s$ is the number of pixels with non-zero colour levels in the standard images. $N_s$ is a ratio value achieved through manual calculation base on the real flow model while $N_R$ is calculated from the generated concentration profile value. Total concentration profile value of full flow is taken for the reference.

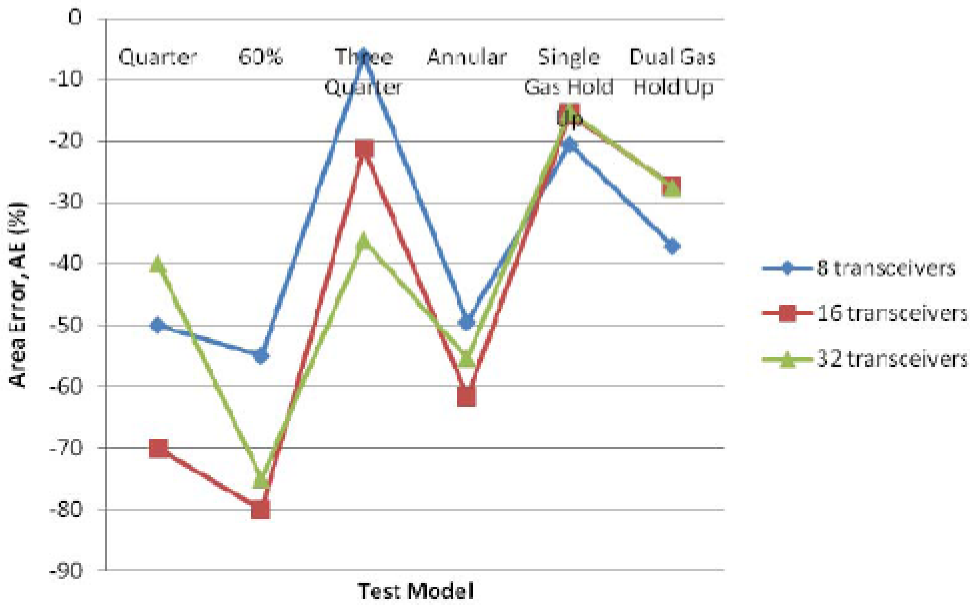


**Fig. 12.** Area error, *AE* of different flow for different numbers of transceivers.

## 10. Discussion

This research provides new technique in ultrasonic tomography by using ultrasonic transceivers instead of using separate transmitter-receiver. This separate ultrasonic transmitter-receiver sensor which is widely used in ultrasonic tomography research required large space when mounted on the surface of the measured area for example pipeline, vessel and so on. This is due to the needs of having pair of the sensors, which is transmitter (to transmit the ultrasonic signal) and the receiver (to receive the transmitted ultrasonic signal). In the separate transmitter- receiver case, the function of each sensor is fixed. This mean that the transmitter is only for transmitting purpose and the receiver is only for receiving. The function of each sensor cannot vice versa. Ultrasonic transceiver has an advantage compare to separate transmitter-receiver in terms of functioning since it has the capability of become a transmitter at one time while can be as a receiver at the other time. Due to this dual functioning, a number of transceiver that mounted on a vessel will have the capability which is almost doubled if the same number of separate transmitter-receiver is used. Thus the resolution of tomographic images that are reconstructed from measurements will be better since it depends on the number of sensors arranged around the flow as well as the spatial resolution of each sensor array [1, 2]. The result given by 32 transceivers are quality enough in determining the types of two phase flow including different position and sizes of gas hold ups in a vessel/pipe line. While image reconstructed through

8 transceivers are the worst since it cannot differentiate the presence of gas hold ups in the pipe but the image is acceptable without the gas hold ups. For 16 transceivers, the images are quite fair since it can detect and differentiate the presence of gas hold ups. The weakness of 16 transceivers is it cannot show clearly the image of gas hold ups with smaller diameter and located nearer to each other. From the result we can see that the area error, *AE* is quite large especially for small volume flow model that are quarter flow, 60% flow and annular flow. This type of problem exists because of the smearing effect in the Linear Back Projection Algorithm (LBPA) due to back projection technique applied. The blurring is due to projection along the straight lines which the intensity distribution is centre symmetrical and dependent on the projection angle where the blurring function is inversed of the corresponding pipe radius. Initial studies showed that this is method effective but further investigations should be continued to extract more quantitative information.

## 11. Conclusions

Transceivers have provided a new low cost technique in non-invasive ultrasonic tomography with low operating voltage as long as the acoustic energy could passes through the process vessel. By increasing the number of transducer it could cater the problem of measurement resolution, spatial image error as well as accurate measurement. The optimum numbers for transceivers of a pipe/vessel in providing good image is 32 transceivers. Instead of better image, the critical draw back to this number of transceivers is the slow of the system due to long time taken to process the data from these transceivers.

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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. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

## Topics Covered

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:

- Physical, chemical and biosensors;
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- Microsystems;
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