Ultrasonic Transmission-Mode Tomography Imaging for Liquid/Gas Two-Phase Flow

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***Abstract*—This paper details the development of noninvasive ultrasonic tomography for imaging liquid and gas flow. The transmission-mode approach has been used for sensing the liquid/gas two-phase flow, which is a kind of strongly inhomogeneous medium. Sixteen pairs of ultrasonic sensors have been used. By using low excitation voltage of 20 V, fan-shaped beam ultrasonic transmitters will emit ultrasonic pulses to the receivers. The investigations were based on the transmission and the reception of ultrasonic sensors that were mounted circularly on the surface of the experimental vessel. The algorithms used to reconstruct the concentration profile for two-phase flow using a fan-shaped beam scanning geometry were presented. By using a hybrid-binary reconstruction algorithm, real-time ultrasonic transmission-mode tomography has been developed. Experiments show that performance is acceptable with an image-reconstruction speed of 10 frames/s. The results of the experiments and possible future improvements were also discussed.**

***Index Terms*—Acoustic imaging, fluid flow measurement, image reconstruction, ultrasonic tomography.**

I. Introduction

REAL-TIME process monitoring plays a dominant role in many areas of industry and scientific research concerning liquid/gas two-phase flow. It has been proved that the operation efficiency of such a process is closely related to accurate measurement and control of hydrodynamic parameters such as flow regime and flow rate [11]. Besides, monitoring in the process industry has been limited to either visual inspection or single point product sampling where product uniformity is assumed.

Ultrasonic tomography has the advantage of imaging two-component flows and gives the opportunity of providing quantitative and real-time data on chemical media within a full-scale industrial process, such as filtration, without the need for process interruption [16]. The major potential benefits are the following: First, it is possible to gain an insight into the actual process. Second, since ultrasonic tomography is capable of online monitoring, it has the opportunity to develop closed-loop control systems, and finally, it can be a noninvasive and possibly nonintrusive system [6]. The overall anticipated effects are improvements in product yield and uniformity, minimized input process material, reduced energy consumption and environmental impact, and lowering of occupational exposure to plant personnel.

An ultrasonic sensor, which is sensitive to the density of sound changes, has the potential for imaging component flows such as oil/gas/water mixtures, which frequently occur in the oil industry. In [11], the authors point out that the ultrasonic techniques, where in such cases, could be used to image the gas component (large density differences), while the capacitance techniques could be used to image the water component (large permittivity difference), thus providing individual images of the gas and water components flowing in an oil well, riser, or pipeline.

The imaging and measurement of flows provide an important inspection method in industrial processes. Ultrasonic tomography enables the measurement of certain characteristics of objects that cannot be easily obtained by other methods. Ultrasounds are able to detect changes in acoustic impedance (Z), which is closely related to the density (ρ) of the media ($Z = \rho c$, where c is the velocity of sound) and thus complements other tomographic imaging technologies such as electrical capacitance tomography and electrical impedance tomography [2]. Ultrasonic tomography has mainly been researched with a reduced number of transducers (commonly two), which are rotated around the objects of interest [6]. These systems cannot produce the rapid data capture that would lead to real-time imaging and measurement of a highly fluctuating target area.

Xu and Xu [18] have published an interesting paper on ultrasonic tomography, where they have developed an ultrasonic-tomography system for monitoring bubbly gas/liquid two-phase flow. The tomography system implements an invasive technique with six transceivers and 36 receivers. They have also derived a two-value logical back-projection filtering algorithm.

The work reported in this paper demonstrates image-reconstruction techniques applied to an experimental vessel using a noninvasive technique. The principle overview is described first. Second, the noninvasive technique of ultrasonic transducer setup is described. Third is the measurement technique, and fourth, the image-reconstruction algorithms are briefly discussed. Experimental results including the image-reconstruction comparison using different algorithms, image-reconstruction error measurement, and result analyses are finally discussed.

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II. Principles Overview

The ultrasonic wave is strongly reflected when it interfaces between one substance and another. However, it is difficult to collimate, and problems occur due to reflections within enclosed spaces such as metal pipes [7]. There are two types of ultrasonic signals that are usually used. They are the continuous signal and the pulsed signal [6]. Using a continuous signal will provide a continuous impact on the crystal, whereas by using pulses, the interval of the transmission and reception signal can be estimated. Using the ultrasonic method in air is very inefficient due to the mismatch of the sensors' impedance as compared with air's acoustic impedance. New types of sensors are continually being developed, but the effective ones are expensive. The design of this sensor is critical when it needs to reduce the sensor's ringing [5].

The sensor system can be classified into transmission-mode, reflection-mode, and emission-mode techniques [12]. The transmission-mode technique is based on the measurement of the change in the properties of the transmitted acoustic wave, which are influenced by the material of the medium in the measuring volume. The change of the physical properties can be the intensity, the polarization, and/or transmission time (time of flight). The reflection-mode technique is based on the measurement of the position and the change of the physical properties of the wave or a particle reflected on an interface. Similar to the reflection-mode technique, there are some techniques based on diffraction or refraction of the wave at a discrete or continuous interface in the object space. The emission-mode technique is based on the measurement of the intensity and the spatial orientation of the radiation emitted from the inside of the measurement plane.

The ultrasonic technique also has potential for multimodal sensing as the technique could be based on the measurement of the energy attenuation and the transmission time (velocity). Examples of ultrasonic techniques for differentiating three-phase components in a gas-liquid-solid system are the use of the ultrasonic-signal analysis method [9], [10], [14] and the multifrequency ultrasonic technique [15].

In the other view, ultrasonic tomography poses a problem where the real-time performance is paramount: the complex sound field sensed by transducers often result in overlapped or multiple reflected pulses which introduce errors; and the inherent slow propagation speed of ultrasound lowers the scanning speed. To eliminate these problems, Li and Hoyle [8] presented a spectral analysis strategy, which examined the phase information of the reflected ultrasonic signal detected by a transducer. A circular detector array was used to enable the real-time data acquisition. Warsito *et al.* [16] had mentioned some considerations in implementing the transmission-mode ultrasonic technique to gas–liquid–solid systems. There are two major constraints on the application of the transmission-mode ultrasonic technique.

1) *Limitation by attenuative media:* As a gas–liquid (the reflection rate almost 100%) or a liquid–solid interface (the reflection rate about 90%) is almost a perfect mirror for an acoustic wave, the present tomography system can only be used in case of sparse bubbly or particulate systems. When the number of bubbles and/or the particles over the cross section is too large and the projection area of the bubbles and/or the particles on the cross section of the transducer becomes larger than the axial aperture, there will be not enough space for the acoustic beam to pass through and arrive at the corresponding receiver along a straight path. Therefore, total holdups (gas and solid) of up to 20% may be a reliable limit for the application of the measuring technique. Attenuation caused by a viscous liquid or a long transmission path may be overcome by the use of a more powerful ultrasonic generator or amplifier.
2) *Limitation by complex sound field:* The complex sound field sensed by transducers could result in overlapped or multiple reflected pulses, which introduce errors in the measurement. To avoid this, the most common approach is to use only the first time-of-transmission signal corresponding to a straight path, as the reflected signal will be detected after the first time-of-transmission signal. The uses of a high frequency and a planar signal by allowing a free-bubble region between the transducer and the measuring volume (coupling) will also decrease multiple scattering.

III. Ultrasonic Transducer Setup

In solids, ultrasonic waves can propagate in four principle modes that are based on the way the particles oscillate. Ultrasonic waves can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. In liquid and gas media, an ultrasonic beam advances as a longitudinal wavefront, which is in common with all sound waves. However, at surfaces and interfaces, various types of elliptical or complex vibrations of the particles make other waves possible. Some of these wave modes are the Rayleigh and Lamb waves. Lamb waves are a complex vibrational wave that travels through the entire thickness of a material. Propagation of Lamb waves depends on the density, elasticity, and the material properties of a component, and they are influenced by selected frequency and material thickness [4].

Using the ultrasonic method in air is very inefficient due to the mismatch of the sensors' impedance as compared to air's acoustic impedance. Therefore, an acoustic coupling is introduced between the sensor's surface and the outer pipe wall. The purpose of the couplant is to provide a reliable transmission of ultrasound between the transducers and the pipe wall. Different couplants are used for long- and short-term uses. The long-term types are essentially Araldites, Eurothane resins, and Epoxy resins without fillers that will diffuse the sound. Short-term types are silicon grease and axle grease. With a short-term couplant, it is important to ensure that it does not dry out. It is recommended that a thin bead of couplant, which is about 5 mm by about 3–4-mm deep, is run along the transducer and then compressed onto the pipe. Pipe surface preparation must be carefully done to preserve the original curvature of the pipe. It is important that the transducer faces and the pipe axis are parallel as one degree error could lead to an approximately 1% change in path length [13].

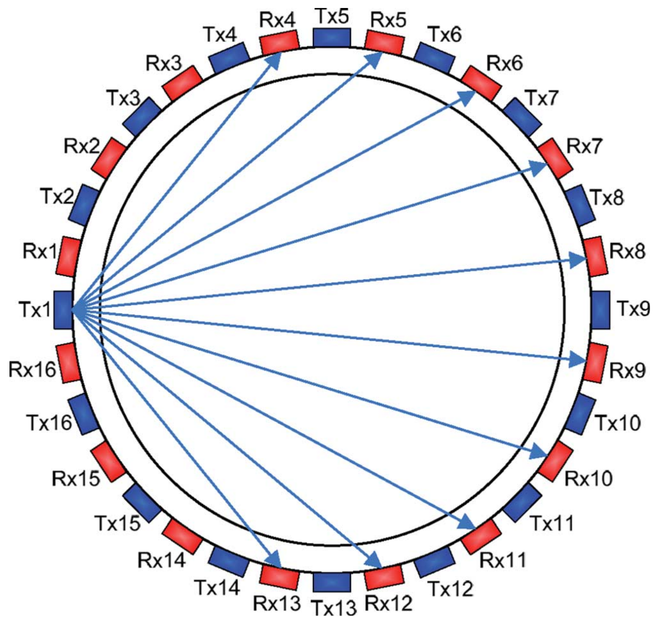


Fig. 1. Measurement section.

Moreover, the coupling will also provide a free-air region between the sensor's surface and the pipe wall [1]. This is because, in air, the acoustic energy will be scattered, and thus, none of the transmitted signals could pass through the pipe. In this research, Glycerin, which is very fine grease, is chosen to be the couplant. It was sandwiched between the sensor's surface and the outer pipe wall.

An acrylic pipe with a 115-mm outer diameter and a 6-mm pipe wall thickness is used as the experimental vessel. Ultrasonic transducers will be evaluated by circularly arrayed 16 pairs (16 transmitters and 16 receivers) noninvasively on the surface of the experimental vessel. The active elements for these transducers are piezoelectric ceramic with a resonant frequency of 40 kHz. The measurement section is shown in Fig. 1.

$Tx1$, $Tx2$, $Tx3$, etc., represent the transmitters, whereas $Rx1$, $Rx2$, $Rx3$, etc., represent the receivers. By using the transmission-mode method and the fan-shaped beam projection technique, the ultrasonic transmitters will transmit pulses at 40 kHz through the process vessel to the point of interest. Each transmitter excited will emit two cycles of tone burst of 40 kHz at 20 Vp-p. These transducers, having divergence angle α of 125°, resulting from each projection from the transmitting transducers, cover up to ten channels of the receiving transducers. A total of 16 observations were made in one scan; hence, 160 independent measurements were obtained.

IV. Measurement Technique

An example of the received ultrasonic waveform is shown in Fig. 2.

In Fig. 2, the observation time denoted by t_{s} was the first peak of the first time-of-transmission signal corresponding to a straight path. When the components to be imaged are gas, there may be no directly transmitted signals from the transmitter to the receiver because of the obstacle. By reflecting against the pipe wall or multiple reflections on the gas component surfaces, the receiver may still detect some signals, at a later time though, because a direct transmission takes the shortest path and, hence, the shortest time [3]. Thus, if the observation time is monitored, it is easy to test whether there are any objects in between the transmitter and the receiver. This is the concept of the transmission mode that is proposed in this paper. Fig. 3 shows three possible paths for the receiving signals.

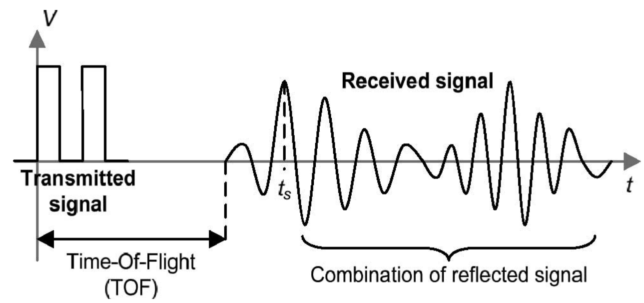


Fig. 2. Example of a transmitter and a receiver signal.

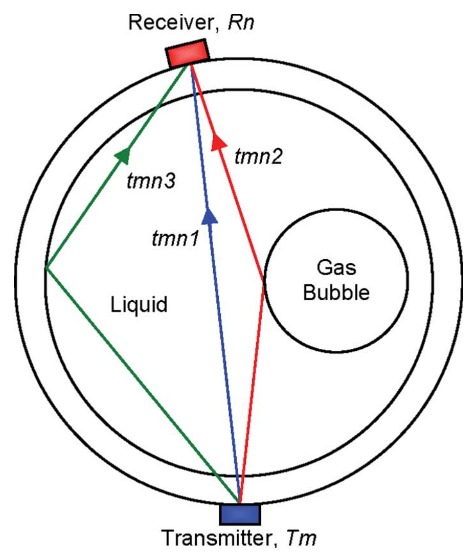


Fig. 3. Three possible paths for receiving signals.

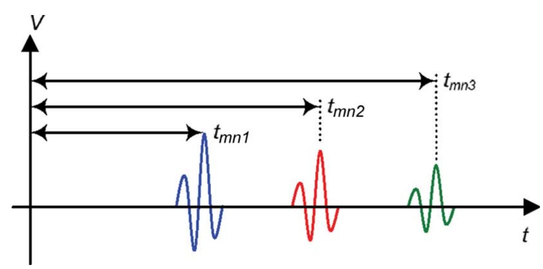


Fig. 4. Receiving signals for different sound paths.

The receiving signals may come from the direct transmission (t_{mn1}), the reflected signals by gas component surfaces (t_{mn2}), and the reflected signals against the pipe wall (t_{mn3}). By referring to Fig. 3 as an example, it is found that the shortest path will provide the shortest observation time which is t_{mn1}. The reflected signals t_{mn2} and t_{mn3}, however, will arrive later. The delay between each receiving signal is represented in Fig. 4.

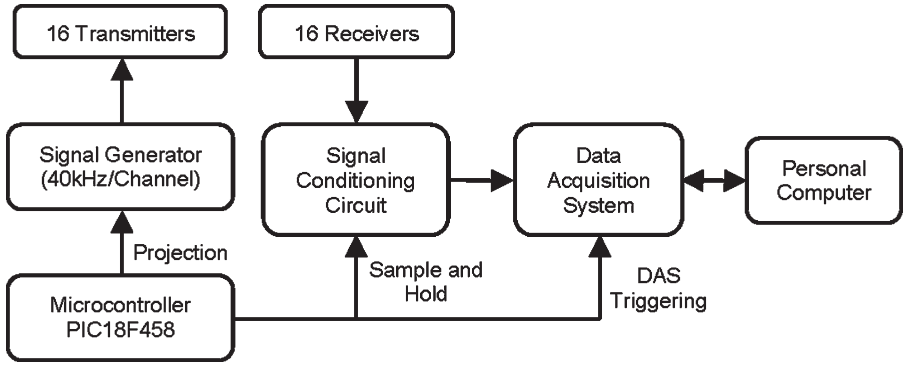


Fig. 5. Electronic measurement system.

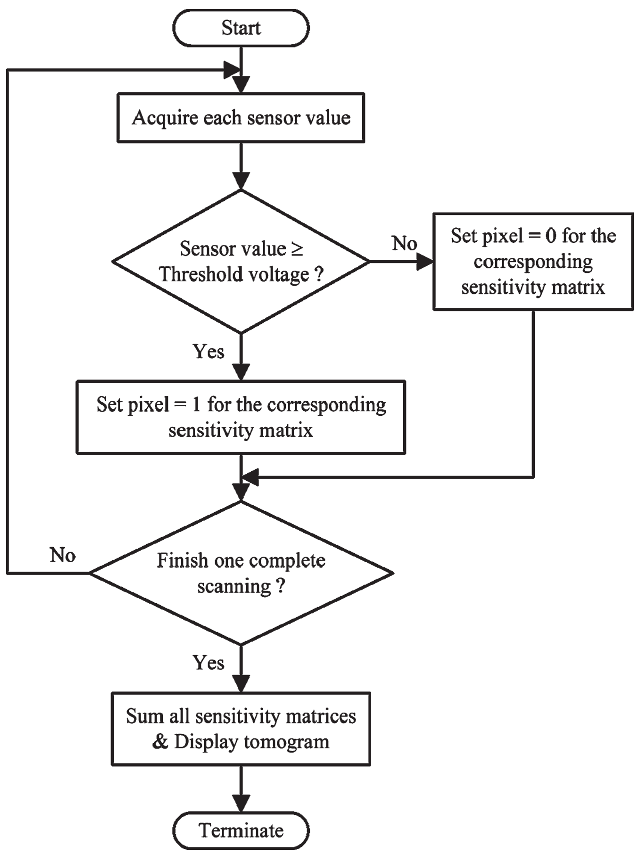


Fig. 6. Flowchart for the HBR.

When a pulse is transmitted from the transmitter, for each receiver, there is a specific observation time at which the transmitted pulse should arrive. This time is the shortest time, and the path between the transmitter and receiver is a straight line. This observation time for each receiver is recorded and programmed into the microcontroller.

The electronic measurement system block diagram is shown in Fig. 5. A PIC18F458 microcontroller was used to control the projection of 40-kHz pulses at rate of 200 Hz between each transmission. These pulses were then fed into comparators to create 20-V pulses to the ultrasonic transmitters. The received signals were then amplified to an appropriate voltage level. A received signal, which has been directly transmitted, can therefore be distinguished from a reflected signal, which must have a longer delay time. If a directly transmitted signal is detected, it can be concluded that there are no gas holdups between the transmitting and receiving transducers.

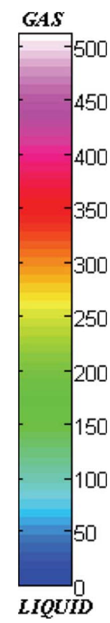


Fig. 7. Color gradient for tomogram.

A sample-and-hold technique was used to capture (sample) the receiver signal at the determined observation time and hold it to an appropriate delay under the control of an external circuit (microcontroller). These sampled signals were acquired into the PC using data-acquisition system for further processing.

V. Image-Reconstruction Algorithm

Most of the work in the process tomography has focused on the use of linear-back-projection (LBP) algorithm. It was originally developed for X-ray tomography, and it also has the advantage of low-computational 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. The process of obtaining the concentration profile using the LBP can be expressed mathematically as

$$V_{\mathrm{LBP}}(x,y) = \sum_{Tx=0}^{m} \sum_{Rx=0}^{n} S_{Tx,Rx} \times \overline{M}_{Tx,Rx}(x,y) \quad (1)$$

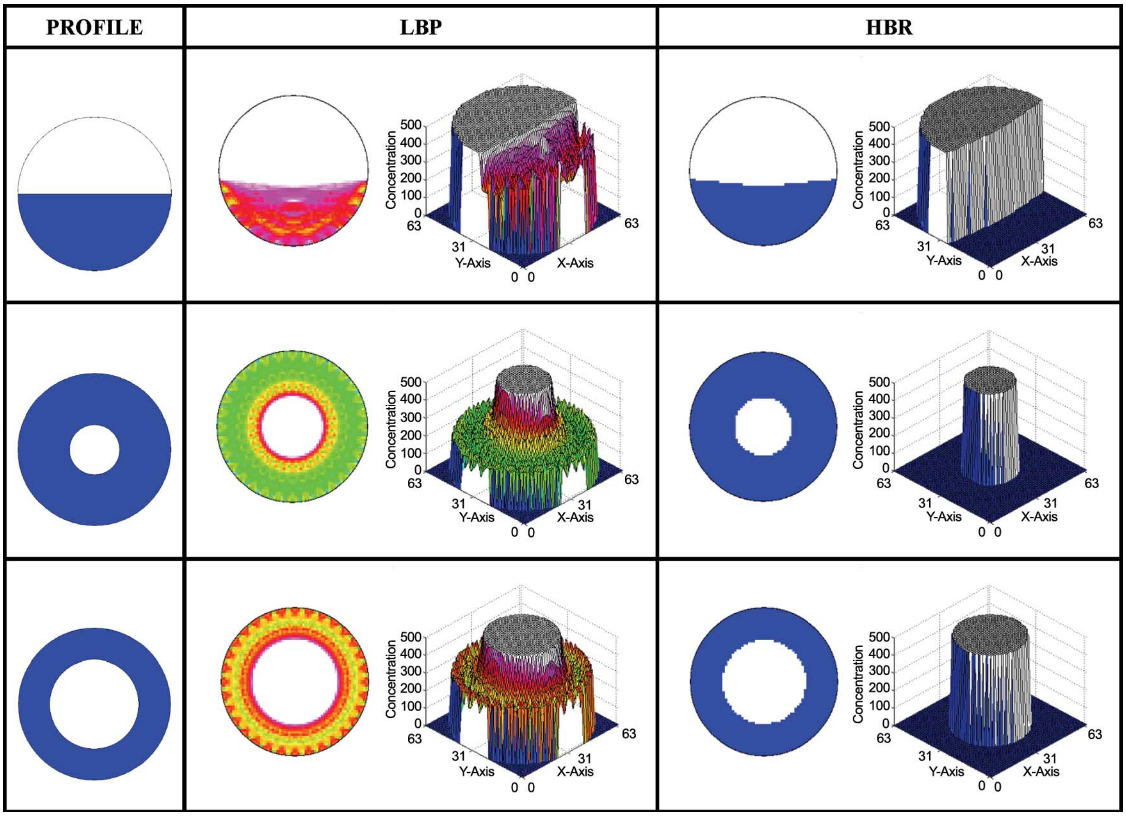


Fig. 8. Simulation of test profiles.

where $V_{\mathrm{LBP}}(x,y)$ is the voltage distribution on the concentration profile matrix, $S_{Tx,Rx}$ is the sensor loss value, and $/M_{Tx,Rx}(x,y)$ is the normalized sensitivity matrices.

For comparison with the LBP method, a second image-reconstruction technique has been employed, namely, the hybrid-binary reconstruction algorithm (HBR). This algorithm has the advantage of improving the stability and repeatability of the reconstructed image. This algorithm eliminates unused sensitivity matrices that cause the blurring image and distinguish the image background. A threshold voltage (V_{Th}) is needed for the purpose of separating the object from the background, thus creating a binary picture from a picture data (tomogram). A threshold corresponding to half blockage has been set. When sensor values are lower than the threshold, it will be discarded. This procedure is appropriate for two-phase flow imaging in cases where the phases are well separated such as liquid-gas flow [11]. The reconstruction method is represented in Fig. 6. This algorithm determines the condition of projection data and improves the reconstruction by marking the empty area during reconstruction [7]. The algorithm assumes binary values from the sensors: either zero for the gas section or one for the liquid section. If the sensor value equals zero, then any pixels traversed by that sensor's beam are set to zero and omitted from further calculations. The mathematical model for HBR is shown as

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

in which

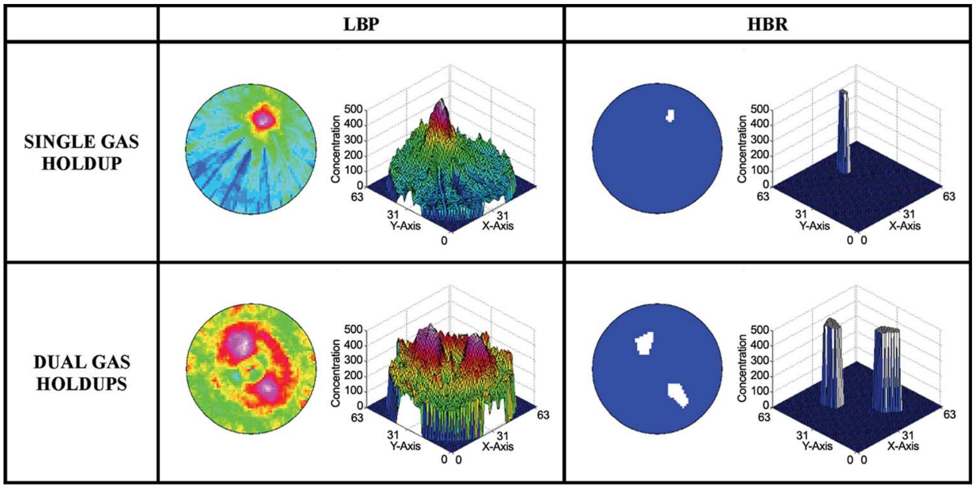
$$\begin{aligned} V_{\mathrm{HBR}}(x,y) &= 0 \qquad \Rightarrow V_{Tx,Rx} < V_{\mathrm{Th}} \\ V_{\mathrm{HBR}}(x,y) &= 511 \quad \Rightarrow V_{Tx,Rx} \geq V_{\mathrm{Th}} \end{aligned} \tag{3}$$

where $V_{Tx,Rx}$ is the sensor value, and $V_{\mathrm{HBR}}(x,y)$ is the concentration profile obtained using HBR.

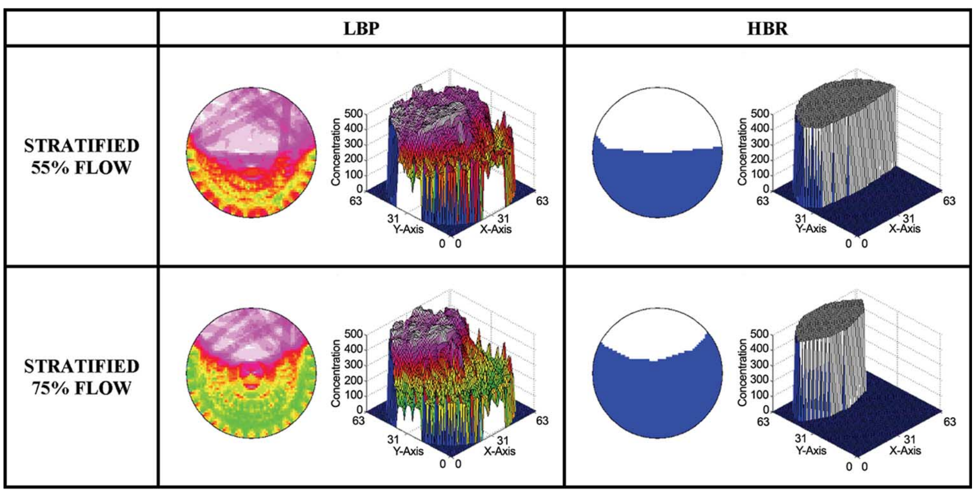
VI. Reconstruction Results

The HBR and LBP algorithms have been tested with a number of test profiles. The reconstruction results obtained for a half flow model and small and large annular flow models based on Fig. 7 color gradients are represented, respectively, in Fig. 8.

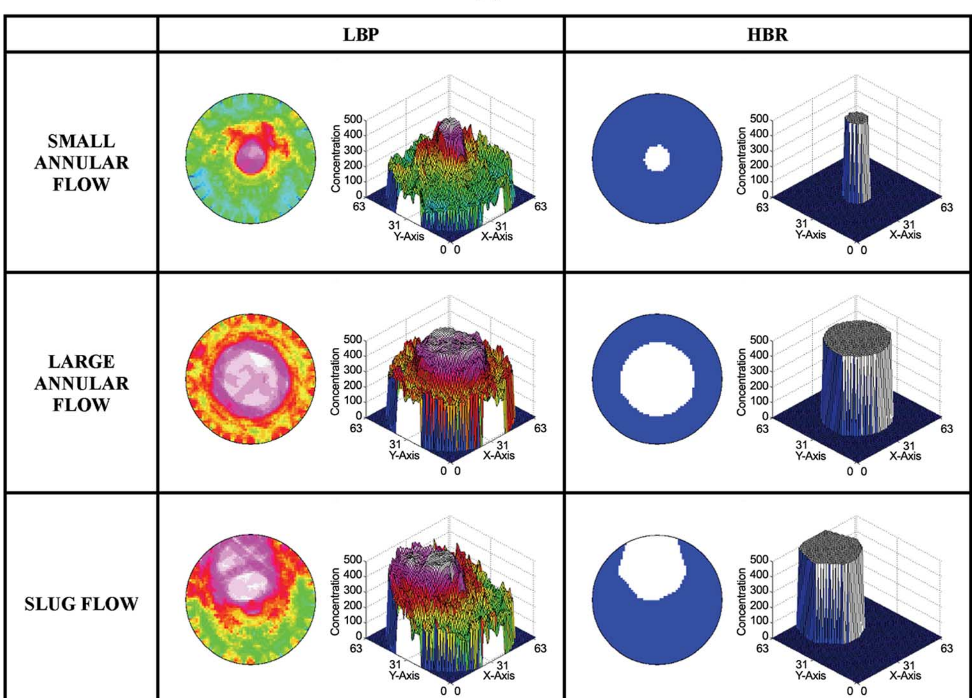
The hardware system is capable of producing 300 frames/s, and the image-reconstruction speed is 10 frames/s. This system was tested using static physical models simulating the typical distribution patterns of two-component flow. Fig. 9(a)–(c) showed some of the images that the system reconstructed using the LBP algorithm and the HBR algorithm. The results showed the reconstructed images for single gas holdup, dual gas holdups, stratified flow, annular flow, and slug flow. A small circular tube representing the gas model was placed inside the experimental pipe to simulate the gas holdup. A horizontal pipe with a static liquid model was used to simulate a stratified flow. For annular flow, the image was obtained when an empty circular tube (gas model) was put in the center of the pipe, and



(a)



(b)



(c)

Fig. 9. (a) Image reconstructed for single and dual gas holdups. (b) Image reconstructed for stratified flows. (c) Image reconstructed for annular and slug flows.

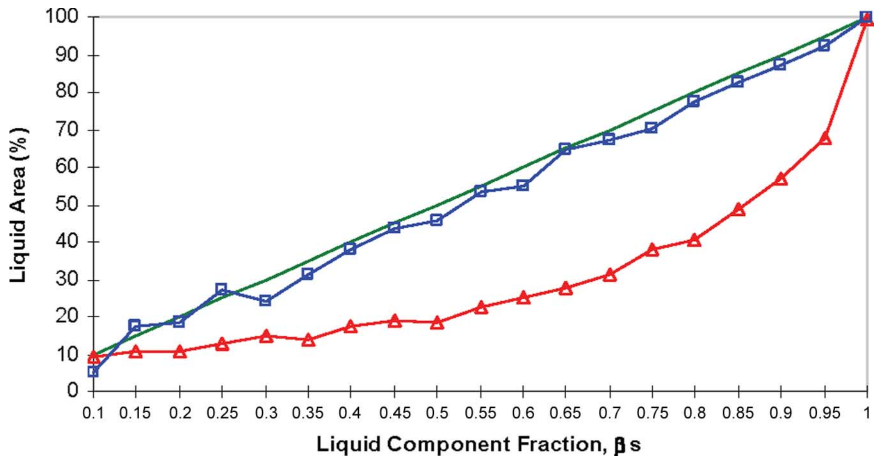


Fig. 10. Liquid area percentage for stratified flows.

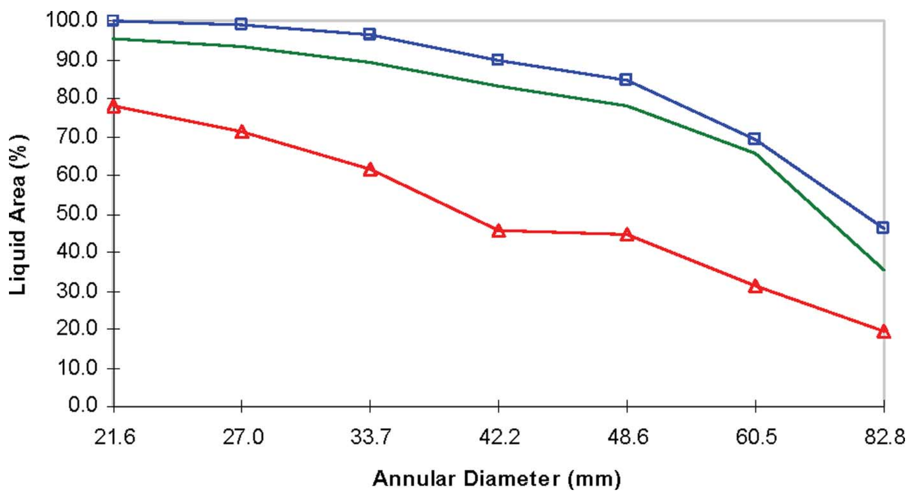


Fig. 11. Liquid area percentage for annular flows.

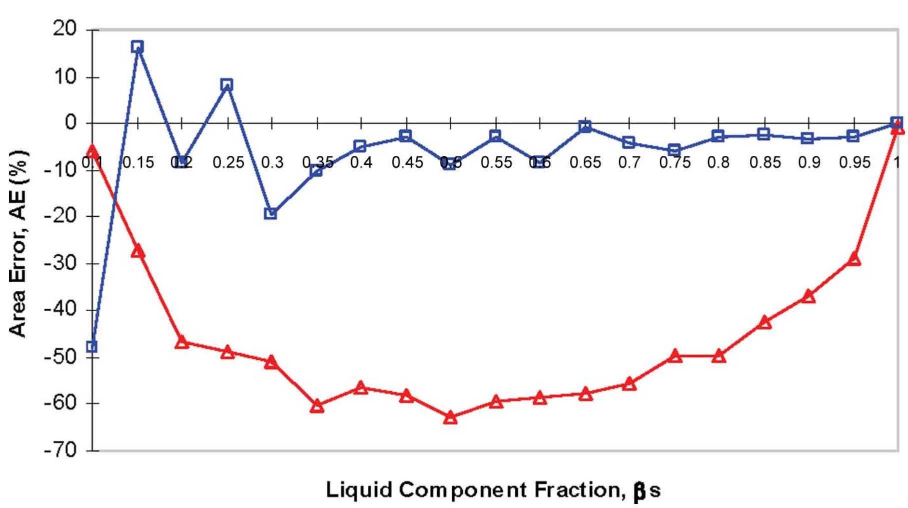


Fig. 12. Area error for stratified flows.

the gap between the tube and pipe was filled with liquid. The cross-sectional image of a slug flow was obtained when the tube was placed near the pipe wall.

The quality of a tomographic flow imaging system can be judged by comparing the reconstructed image of a physical model with the actual cross section. The comparison is performed on the image-reconstruction computer against a standard image (test model) which matches the cross section of the physical model. Ideally, the reconstructed image (Fig. 9) should be identical to the standard image (the test model),

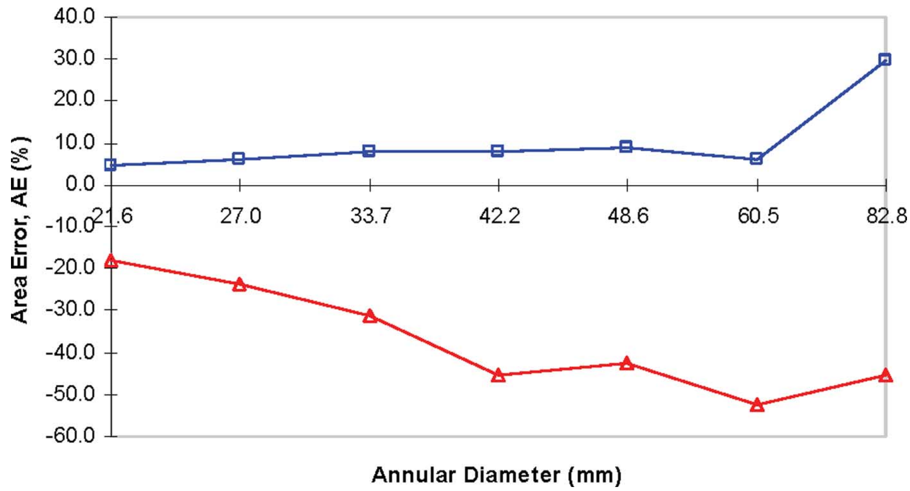


Fig. 13. Area error for annular flows.

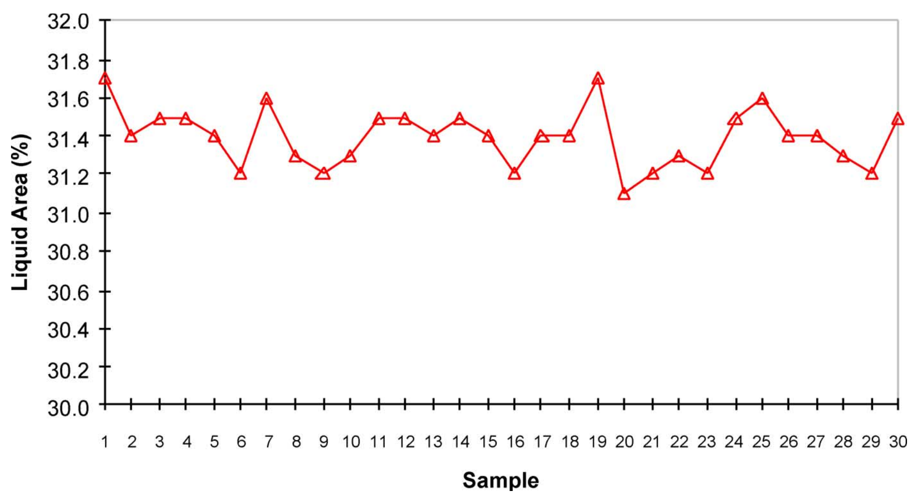


Fig. 14. Repeatability measurement for LBP.

but in practice, differences arise. To quantify these differences, error information is obtained using the area error AE, which is defined as [17]

$$\mathrm{AE} = \frac{\sum_{p=1}^{M} G_{\mathrm{B}}(p) - \sum_{p=1}^{M} G_{\mathrm{S}}(p)}{\sum_{p=1}^{M} G_{\mathrm{S}}(p)} = \frac{N_{\mathrm{R}} - N_{\mathrm{S}}}{N_{\mathrm{S}}} = \frac{N_{\mathrm{R}}}{N_{\mathrm{S}}} - 1 \quad (4)$$

where $G_{\mathrm{B}}(p)$ is the binary reconstructed image pixels, $G_{\mathrm{S}}(p)$ is the standard (test) model pixels, N_{R} is the number of pixels with nonzero color levels in the reconstructed images, and N_{S} is the number of pixels with nonzero color levels in the standard images. Several experiments simulating the stratified flow and the annular flow have been conducted, and the error measurements have been calculated. Liquid area percentages from stratified flow and annular flow experiments are compared with the standard models and shown in Figs. 10 and 11, respectively. For the stratified flow area errors, they are represented in Fig. 12, whereas the annular flow area errors are represented in Fig. 13. Experiments for the repeatability of the reconstruction algorithms were also conducted. These experiments measure the stability performance of those algorithms on reconstructing cross-sectional images of the corresponding flows. Therefore, 30 sets of continuous data for a static annular flow that are 60.5 mm in diameter have been captured. Fig. 14 shows the repeatability of the LBP technique, whereas Fig. 15 shows the repeatability of the HBR technique.

VII. Conclusion

Noninvasive ultrasonic tomography for liquid/gas two-phase flow had been developed and investigated. Experimental results showed that this system could be used to identify the flow pattern and measure the cross-sectional void fraction. This system showed that low-operating voltage transducers are sufficient for performing the measurement as long as the acoustic energy could pass through the process vessel. Thus, high-voltage (hundreds of volts) excitation is no longer needed, and it cuts down on transducer design limitations. By simply increasing the number of the transducers, it could cater to the problem of measurement resolution, spatial image error, as well as accurate measurement. The hardware is capable of producing data at 300 frames/s, but data transmission and image reconstruction only make it possible to observe images at

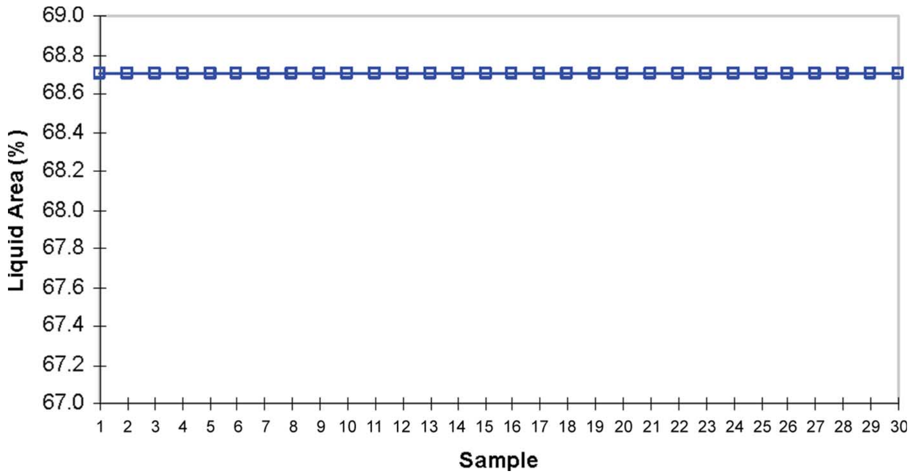


Fig. 15. Repeatability measurement for HBR.

10 frames/s. Improvements in the reconstruction program would make it possible to capture images faster than the present setup. Static experiments were carried out to estimate the performance of the system presented. Initial studies showed that this method is effective and feasible, but further investigations should be continued to extract more quantitative information.

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