Application of an Ultrasonic Array Sensor to Air-water Bubbly Flow Measurement

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Abstract. The ultrasonic array sensor, which has been successfully applied in the field of medical diagnostics and non-destructive testing, was applied to single-phase and two-phase flow measurement. The applied array sensor has 128 elements on the surface and each of them has a basic frequency of 8 MHz. Flow measurement using the array sensor is very effective, because it can obtain the cross-sectional flow visualization images from outside the pipe without disturbing flows. In this study, the ultrasonic sound pressure distributions were measured by the sound field measuring system, and the ultrasonic beam characteristics and the grouping effects of elements were investigated from the sound pressure field. The velocity profiles of single-phase flows in a rectangular channel were measured with Ultrasonic Velocity Profiler (UVP) by scanning the parallel ultrasonic beam emitted from the array sensor. Furthermore, an ultrasonic array measuring system, which consists of a pulser/receiver, a multiplexer, an A/D converter and a signal processing device, was developed for the improvement of temporal resolution in bubbly flow measurement using the ultrasonic array sensor. Then the bubble distributions in the channel cross-section were confirmed by using the echo signals reflected from bubbles.

1. INTRODUCTION
Bubbly flows, which appear in many industrial plants, are very interesting phenomena in engineering fields. In the previous investigations of bubbly flows, numerous two-phase measuring techniques have been developed and applied to the measurement of flow structure. In bubbly flows, bubble shapes change with time and bubble coalescence and fragmentation occur. Therefore it is neccessary to obtain the instantaneous information of the position, size and velocity of each bubble. Recently, fast X-ray tomography (Hampel et al., 2005; Prasser et al., 2005) and wire-mesh tomography (Prasser et al., 1998; Richter et al., 2002; Prasser et al., 2005) have received considerable attention as useful techniques for bubbly flow measurement. This is because they have high temporal resolution and they can measure cross-sectional distribution. However, these methods have some disadvantages. The fast X-ray method is suitable exclusively for professional users, and the wire-mesh tomography is an intrusive method which has strong influence on flow field. It is difficult to apply these techniques to real industrial systems. So this study focuses on the measurement using pulse ultrasound. Ultrasonic measurement has such advantages as being non-intrusive, applicable to opaque fluids and pipes, low cost, simplicity and ease of use, and it can obtain several major parameters on the measuring line. Murakawa et al. (2007) measured the velocity profiles of air-water bubbly flows in a circular pipe by the ultrasonic Doppler method. They measured velocity profiles of both gas and liquid phases with a
multi-wave transducer. Furthermore, Wada et al. (2006) investigated the flow patterns of gas-liquid two-phase flows, which are bubbly flow, slug flow and annular flow, by using the reflected ultrasonic echo signals from the flows.

Cross-sectional measurement using ultrasonic pulses requires a lot of ultrasonic transducers. Thus, installation errors may be larger, and the system becomes complex. An ultrasonic array sensor, which has been applied in many fields, can resolve these problems. In the field of medical diagnostics, the array sensor is used for imaging cross sections within a living body. And the sensor can detect flaws in a sample and recognize their location.

In this study, the ultrasonic array sensor, which can emit pulse ultrasound over the cross-section, is applied to the measurement of single-phase flows and bubbly flows in a rectangular channel. The ultrasonic sound pressure distributions are measured to understand the ultrasonic beam characteristics when the elements are or aren’t grouped. The cross-sectional averaged velocity profiles in single-phase flows are measured by the ultrasonic velocity profiling method (Takeda, 1986) in order to confirm the validity of ultrasonic array measurement. Then air-water bubbly flows are measured by the ultrasonic echo technique using the ultrasonic array sensor, pulser/receiver and multiplexer, and the temporal resolution of the ultrasonic array measurement is improved.

2. ULTRASONIC LINEAR ARRAY SENSOR

2.1 Applied Ultrasonic Array Sensor

An ultrasonic linear array sensor (Fig. 1) was developed for ultrasonic array measurement of the flow field. The array sensor has 128 piezoelectric elements which can work individually. The arrangement of these elements is illustrated in Fig. 2. Each element has a size of 1mm × 3mm, so the effective size of this sensor is 128mm × 3mm. The frequency bandwidth is about 5 to 8 MHz. In this study, the frequency of 8 MHz is applied to the measurement because of its higher spatial resolution. In the future, this sensor will be applied to the phased array system for wide area scanning and inclined beam formation.

![Fig. 1 Photograph of applied array sensor](image-url)
2.2 Ultrasonic Beam Characteristics

2.2.1 Sound Field Measurement System
The sound pressure field of pulse ultrasound transmitted into water is important in investigating the ultrasonic beam characteristics (e.g. Measurement volume, measuring area and reflected intensity). In this study, sound pressure measurement is performed by the hydrophone technique. Fig. 3 shows the schematic diagram of sound pressure field measuring system. This system consists of pulse transmitting devices (a pulser and an ultrasonic array sensor), receiving devices (an ultrasonic hydrophone and an A/D converter), a three-dimensional stage and a water bath. The pulse signal sent from the pulser is transmitted into water by the ultrasonic sensor. The pulse ultrasound with a frequency of 8 MHz was used for sound pressure field measurement. The transmitted pulse signal has 8 cycles per pulse. The water temperature is maintained at 30 degrees Celsius by the thermostatic water bath. At this temperature, the sound speed in water is 1510 m/s. The ultrasonic hydrophone fixed on the 3-D stage is traversed in the test region and it receives the electrical signals with the piezoelectric element of the hydrophone. This element has a detecting area of $1 \times 1 \text{mm}^2$. This technique can measure the time series data of received signals and is applicable to the transmitting path analysis of ultrasonic pulse in three-dimensional space.
2.2.2 Ultrasonic Sound Pressure Distributions

Fig. 4 and Fig. 5 show distributions of ultrasonic sound pressure, as measured with the ultrasonic array sensor. Fig. 4 shows the result of measurement taken from every piezoelectric element on the sensor. Fig. 5 shows the result when every 3 contiguous elements are taken as a unit of measurement. These results revealed a grouping effect of piezoelectric elements taken as a unit of measurement. In these figures, the $x$-axis represents the direction of ultrasonic emission, and the $y$- and $z$-axes show the directions perpendicular to the $x$-axis. The figure (a) is the sound pressure field on $x$-$y$ plane at $z = 0$. The figures (b) and (c) are the cross-sectional distributions of ultrasonic beams at $x = 20$ and $40$ mm.

![Sound pressure distribution measured with one piezoelectric element](image)

(a) $x$-$y$ plane

![Sound pressure distribution measured with a group of 3 piezoelectric elements](image)

(b) $y$-$z$ plane at $x=20$ mm

(c) $y$-$z$ plane at $x=40$ mm

Fig. 4  Sound pressure distribution measured with one piezoelectric element

Fig. 5  Sound pressure distribution measured with a group of 3 piezoelectric elements
respectively. As shown in Fig. 4, when $x$ is less than 10 mm from the front surface of the array sensor, the sound pressure is higher, and the measuring volume is small. However the decrease in the sound pressure and the spreading of the ultrasonic beam are observed when $x$ is more than 10 mm from the sensor. Thus it is better to measure sound pressure in the near field. In Fig. 5, the sound pressure is larger when $x$ is 10 mm to 30 mm. And in this result, the spreading of the beam is less than the use of every element, so the directionality is good. From the results of sound pressure field measurement, the intensity of transmitted beam was estimated. Fig. 6 shows the transition of beam intensity on the beam center line. In the case of every 3 grouped channels, the variation of beam intensity is within 2 dB. However, when a piezoelectric element is individually used, the beam intensity decreases with increasing distance from the sensor, and it is less than -3 dB when $x$ is more than 25 mm. The beam characteristics of ultrasonic pulse transmitted into water can be clarified by measuring the sound pressure field. Therefore the use of every 3 elements is found to be suitable for flow measurement.

3. FLOW MEASUREMENT USING AN ULTRASONIC ARRAY SENSOR

3.1 Experimental Set-up

The experimental apparatus consists of a water-air circulation system, a test section and a measurement system, as shown in Fig. 7. Working fluids are water and air. Water flows into the test channel through a control valve, an orifice flow meter and a flow straightener (0.5 mm mesh stainless plates) by the pump. After water flows through the test section, it overflows and goes back to the storage tank. Water temperature is kept around 20 degrees Celsius by the cooling water. Air is supplied by a compressor. A pressure of air is controlled by a control valve. Air flow quantity is measured by a laminar flow flowmeter. Air inlet is made of five metal needles set at 100 mm downstream from the flow straightener. The outer diameter of each needle is 2 mm and the diameter of holes drilled in each needle is 1 mm. The tip of the needle is round in order to reduce influence on the flow. All the needles are set in parallel to give the same performances.

The measuring section of the ultrasonic array sensor is made of acrylic glass because it has almost the same acoustic impedance as water. In consequence, it is also useful for image measurement. That is the results measured with the ultrasonic array sensor can be compared with those obtained from other optical measurements. (e.g. Particle image velocimetry, Laser Doppler velocimetry). The total length of the test channel is 1,800 mm and the cross section is rectangular, $20 \times 100$ mm$^2$, so the hydraulic equivalent diameter is about 33 mm. To improve the ultrasonic transmission, the thickness of the wall is 1 mm at the measuring section, and the incident angle of the ultrasonic array sensor is 45 degrees. A water box is installed in the measuring section. Water is filled between the array sensor and the outer
For the single phase flow measurement, nylon powders with the diameter of 80 µm and specific gravity of 1.02 are used as ultrasonic reflectors.

3.2 Averaged Velocity Profile Measurement of Single-Phase Flow

Fig. 8 shows the measurement system for velocity profiling using an ultrasonic array sensor. The velocity profiles are measured by the UVP monitor (Met-Flow, UVP-Duo). Two conversion boxes were used to connect the ultrasonic array sensor and UVP. In conversion box1, the ITT-CANON connector is converted to BNC terminal with 128 channels. Here, the 128 elements of the array sensor can operate separately. The conversion box2 was used to put some elements together (Max. 6 channels). Thus, the array sensor is connected with the UVP monitor.

In this study, the cross-sectional average velocity profiles are measured by the array sensor using every piezoelectric element or 3 contiguous elements in order to confirm the grouping effects observed from the sound pressure field measurement. Fig. 9 shows the cross-sectional average velocity profiles measured by the UVP. Fig. 9(a) shows the results when each element worked individually. The velocities on some measuring lines have small irregularity, due to the differences in the sensitivity of each element and the presence of noise. In Fig. 9(b), the 3 contiguous elements are grouped (element No. 1-2-3 is CH.1, element No. 4-5-6 is CH.2…), and the averaged velocity profile can reveal the flow field in the cross-section.
Fig. 8  Ultrasonic array velocity profiling system for single-phase flows

Fig. 9  Cross-sectional average velocity profile (Re=4,000)
3.3 Application to Bubbly Flow Measurement
In the measurement of transient two-phase flows, appropriate temporal resolution is required to clarify the flow phenomena. However, when the UVP array measurement is performed, the temporal resolution of the cross-sectional instantaneous profile depends on the specifications of the UVP monitor. Since the measuring time of cross-sectional velocity distribution using the UVP is no less than about 1 second, their velocity distributions cannot reveal the instantaneous flow field. Therefore, the ultrasonic array measuring system was developed for bubbly flow measurement, as shown in Fig. 10. This system has a multiplexer for switching the pulse signal between the array sensor and the pulser/receiver. The switching time is 6 ms at least. The pulser/receiver has the maximum repetition rate of 8 kHz. The multiplexer and pulser/receiver control the pulse emitting time with a PC, and the received signals were stored in the PC. In this study, the cross-sectional measurement time was improved up to 5 Hz using this system.

The echo signals reflected from bubbly flows are shown in Fig. 11. The reflected signals were obtained by switching the channels of pulse transmission using every 3 contiguous piezoelectric elements of the array sensor, and the positions of bubbles can be detected on the ultrasonic beam from this figure. The cross-sectional distributions are obtained by aligning the echo signals, which were measured by switching each channel in the multiplexer. The cross-sectional echo distributions are shown in Fig. 12. The instantaneous bubble distribution can be measured over the cross-section, and the occurrence and position of bubbles are visualized. Accordingly it was found that the application of the ultrasonic array sensor to bubbly flows leads to the high accuracy bubbly flow measurement. However the temporal resolution of this measurement system is lower than the resolutions of other high-speed measurement system, so further improvements of the system are required for speeding up of channel switching.

![Fig. 10 Ultrasonic array measurement system for bubbly flows](image1)

![Fig. 11 Typical echo signals (CH.4, element No. 13-14-15, \(J_L=0.1\) m/s, \(J_G=20\) mm/s)](image2)
4. CONCLUSIONS

The ultrasonic linear array sensor was applied to single phase and bubbly flow measurement in a rectangular channel. First, the ultrasonic sound pressure distributions were measured to understand the ultrasonic beam characteristics when the elements are or aren’t grouped. Then the cross-sectional averaged velocity profiles in single-phase flows were measured by the ultrasonic velocity profiling method in order to confirm the grouping effect of the elements. Finally, air-water bubbly flows were measured with the ultrasonic echo technique using an array sensor, a pulser/receiver and a multiplexer, and the instantaneous cross-sectional bubble distributions were obtained. However the temporal resolution of the cross-sectional measurement should be improved for much faster measurement.

NOMENCLATURE

\[ J \] superficial velocity \[ \text{[m/s]} \]

\[ \text{Re} \] Reynolds number \[ \text{[-]} \]

\[ x \] coordinate \[ \text{[m]} \]

\[ y \] coordinate \[ \text{[m]} \]

\[ z \] coordinate \[ \text{[m]} \]

**Subscripts**

\[ G \] gas phase

\[ L \] liquid phase
REFERENCES
Hampel, U. et al. (2005). "Experimental ultra fast X-ray computed tomography with a linearly scanned electron beam source," Flow Meas. Instrum., 16, pp. 65-72.

Murakawa, H. et al. (2008). "Application of ultrasonic multi-wave method for two-phase bubbly and slug flows," Flow Meas. Instrum., 19, pp. 205-213.

Prasser, H.-M. et al. (1998). "A new electrode-mesh tomograph for gas-liquid flows," Flow Meas. Instrum., 9, pp. 111-119.

Prasser, H.-M. et al. (2005). "Comparison between wire-mesh sensor and ultra-fast X-ray tomograph for an air-water flow in a vertical pipe," Flow Meas. Instrum., 16, pp. 73-83.

Richter, S. et al. (2002). "Approach towards spatial phase reconstruction in transient bubbly flow using a wire-mesh sensor," Int. J. Heat Mass Trans., 45, pp. 1063-1075.

Takeda, Y. (1986). "Velocity profile measurement by ultrasonic Doppler shift method," Int. J. Heat Fluid Flow, 7, pp. 313-318.

Wada, S. et al. (2006). "Pattern recognition and signal processing of ultrasonic echo signal on two-phase flow," Flow Meas. Instrum., 17(4), pp. 207-224.