Two-phase flow monitoring using ultrasonic multi-wave technique

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Two-phase flow has been recognized as one of the most important phenomena in fluid dynamics. In order to clarify the flow structure, two-phase flow parameters have been measured by using many effective measurement techniques. The velocity profile as one of the important flow parameter has been measured by using ultrasonic velocity profiling technique. This technique can measure velocity distributions along a measuring line, which is a beam formed by pulse ultrasounds. Furthermore, a multi-wave sensor with more than two oscillators can measure the velocity profiles of both gas and liquid phase by separating the reflected echo signals. In this study, multi-wave sensors are applied to air-water bubbly flow monitoring. At first, the transmitted sound pressure fields were investigated to apply these sensors to flow measurement by experimental and numerical approaches, and the beam formation was estimated. Then, the echo signals reflected from air-water bubbly flow in a vertical rectangular channel were measured by using the sensors, and the flow structures were estimated from statistical analysis and velocity profiling process of echo signals.

Keywords: Two-phase flow, ultrasonic velocity profile measurement, multi-wave sensor

1 INTRODUCTION

Gas-liquid two-phase flow is a flow phenomenon which usually appears in the nuclear and thermal power plants, and it is one of the keys to the proper operation of many instruments in the plants. For the clarification of gas-liquid two-phase flow, the experimental studies have been performed. In conventional studies, a number of measuring techniques have been developed and investigated in order to clarify the flow structure. As one of the most effective two-phase flow monitoring method, wire-mesh tomography (WMT) has been developed [1] and applied to many two-phase flow measurements. In WMT, two-phase flow parameters (instantaneous void fraction distribution, bubble size and bubble velocity etc.) can be estimated by measured electrical conductivity between crossing wires. However, the intrusive effect to the bubble velocity cannot be ignored [2]. Therefore, the authors focused on ultrasonic velocity profiling (UVP) technique not only for the bubble velocity measurement but also for the liquid measurement. As the previous studies, UVP method has been successfully applied to air-water bubbly flow measurement with multi-wave sensor which has more than two oscillators [3]. In addition, as a high time-resolution UVP technique, ultrasonic time-domain cross-correlation (UTDC) method has been developed and applied to flow measurement [4].

In this study, multi-wave sensors are used for multi-wave ultrasonic velocity monitoring in two-phase bubbly flow. The ultrasonic sound field transmitted into water is important to improve the UVP measurement accuracy, because the measuring volume is defined by the beam diameter and channel distance. As the previous study, sound pressure distributions have been investigated by experimental method. So the ultrasonic transmission characteristics of multi-wave sensors are investigated by experimental and numerical analysis, and the effect on the measurement volume or ultrasonic beam formation is evaluated. In air-water bubbly flow in a vertical rectangular channel, the echo signals are measured and the bubble velocity profiles are estimated by using UTDC algorithm.

2 CHARACTERISTICS OF ULTRASONIC TRANSMISSION

2.1 Sound field measurement

The sound pressure distributions transmitted into water were measured by the hydrophone technique. This system consists of a pulser devise, a receiver device, an automatic 3D stage and a thermostatic water bath, as shown in Fig.1. The pulse signal sent from pulser is transmitted into water by the sensor. 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.

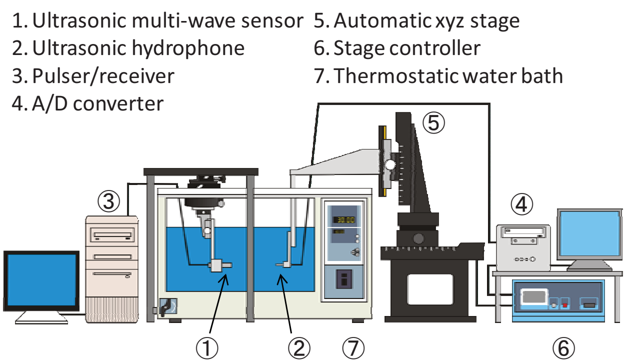


Figure 1: Schematic diagram of sound field measurement system.

The ultrasonic hydrophone fixed on the 3D stage was 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 1×1mm^2. This technique can measure the time series data of received signals and it is applicable to the transmitting path analysis of ultrasonic pulse in three-dimensional space.

2.2 Sound field calculation

The numerical analysis of the sound field was carried out to compare with the measurement and to obtain smaller spatial resolution. The sound pressure *p* is given by Rayleigh equation, as shown in the following equation.

$$P = \rho \int_{S_T} v'_T \left(t - \frac{r}{C} \right) \frac{dS}{2\pi r} \tag{1}$$

The Rayleigh equation with ring function [5] was applied to simplify the calculation and to reduce the time in sound field calculation. From this numerical analysis, the spatial sound pressure distribution and the temporal change of ultrasonic pulse can be estimated.

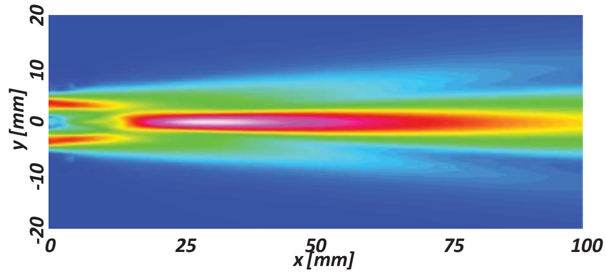
2.3 Sound pressure distributions

The measured and calculated sound pressure distributions with 2MHz multi-wave sensor are shown in Fig.2. The color map represents the intensity normalized by the maximum value of detected voltage in the test area. There are only a few differences between experiment and simulation. It may result in the hydrophone size. This means that the size of 1mm^2 is little bit small in the experiment. From this sound field estimation, it shows that there is a weak area of ultrasonic intensity in the near region. This sound pressure attenuation attributed to the doughnut-shaped element of the 2MHz multi-wave sensor.

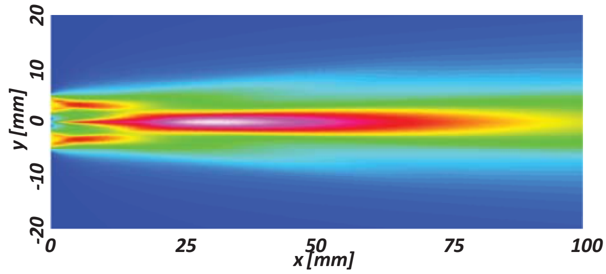
The 3D distributions of ultrasonic beam with iso-surface of -3dB of maximum pulse intensity are shown in Fig.3. Although the beam of the normal sensor has good shape, the beam near the sensor (x=0~20mm) becomes bicylindrical shape in multi-wave sensor. It is called “hollow effect”. In these regions, it is difficult to define the measurement volume. However the beam after x=20mm has single cylindrical shape and a nearly-constant diameter. Therefore, the ultrasonic beam without hollow effect should be used for the flow measurement.

3 EXPERIMENTAL SET-UP

The experimental set-up consists of an air-water circulation system, a test channel section and a measurement system, as shown in Fig. 4. Working fluids are air and water. Water temperature is kept around 20 degrees Celsius by the cooling water. Air flow quantity is measured by a laminar flow flowmeter. Air inlet is made of 5 metal needles set at

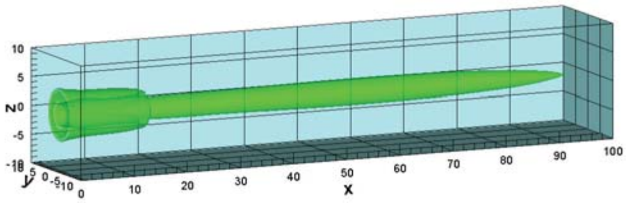


(a) Experimental result

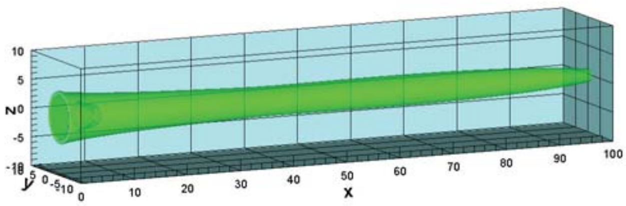


(b) Calculation result

Figure 2: Comparison of sound pressure distributions measured and calculated in *f*=2MHz, 2cycle/pulse, D_{out}=1mm and D_{in}=3mm.



(a) 2MHz multi-wave sensor



(b) 2MHz normal sensor

Figure 3: 3D sound field calculating results in *f*=2MHz, 2cycle/pulse, D_{out}=1mm and D_{in}=3mm.

100mm 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. In this study, gas flow rates from 5 nozzles were controlled individually and non-uniform distribution was formed in the test section with G1~G5, as shown in Fig.5.

The total length of the test channel is 1,800 mm and the length between gas injection and test section is about 1,200 mm. The channel cross section is rectangular, 20×100 mm^2, so the hydraulic equivalent diameter is about 33 mm.

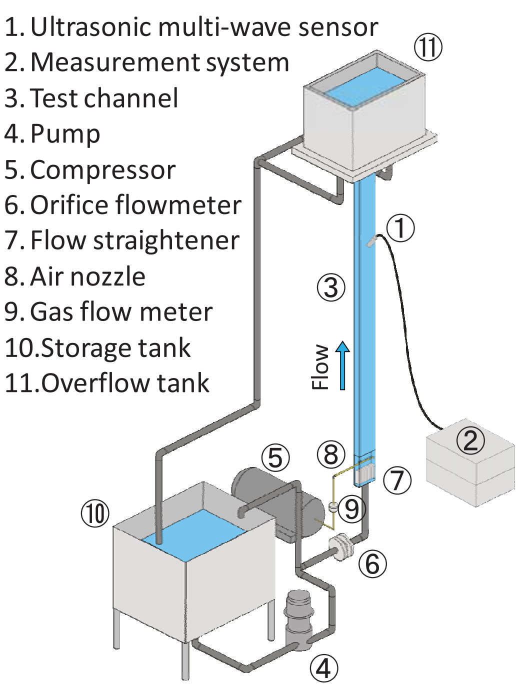


Figure 4: Schematic diagram of experimental set-up.

Table 1: Flow condition

Working fluid	Air, water
System pressure	Atmosphere
Superficial liquid velocity	0.1 m/s (constant)
Superficial gas velocity	1 ~ 5 mm/s (varied)
Temperature of water	20 °C

The measuring section with the ultrasonic multi-wave sensor is made of acrylic glass because it has almost the same acoustic impedance as water. In consequence, it is also useful for image or optical measurement. An ultrasonic multi-wave sensor was set up at 45 degrees in the outside of the channel and the wall thickness of test section was 1mm due to increase the transmission intensity of ultrasound and to decrease the influence of the reflected echo from the wall. Furthermore, as the results of ultrasonic sound field analysis, the ultrasonic beam without the hollow effect was applied to the measurement using 2MHz multi-wave sensor. The multi-wave measurement system is illustrated in Fig.6. A pulse ultrasound is transmitted from the sensor connected to an ultrasonic pulser/receiver (TIT-10B-USB; Japan Probe) controlled by PC. After the ultrasonic pulse was transmitted, the same element detects a reflected echo from an interface of water and bubbles, and then the signal amplified by the receiver was recorded using a digital oscilloscope (WaveRunner 44Xi; LeCroy). The measured signals were analyzed by statistical work and UTDC method.

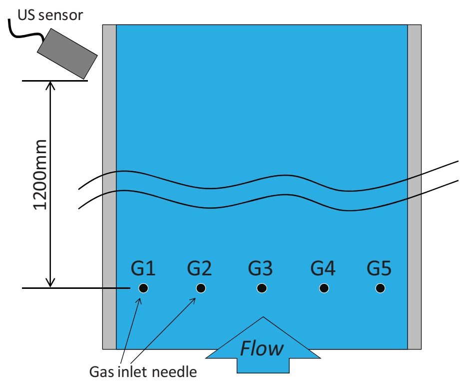


Figure 5: Air nozzle and gas inlet condition.

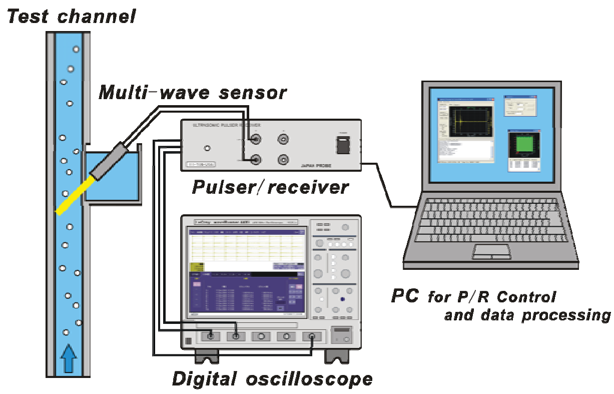


Figure 6: Ultrasonic multi-wave measurement system.

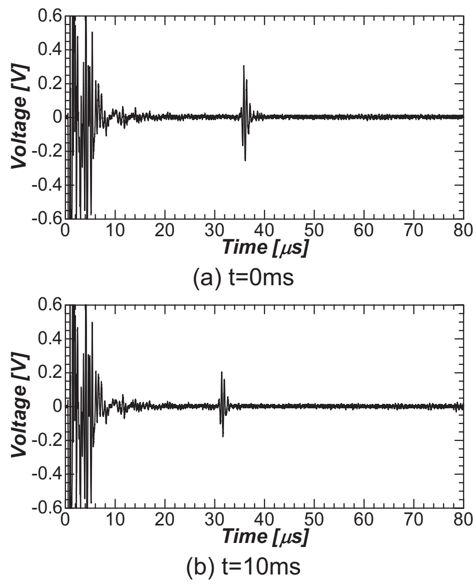


Figure 7: Typical instantaneous echo signals reflected from bubbles (J_G=5mm/s).

4 RESULTS AND DISCUSSION

The typical echo signals reflected from bubbly flows are shown in Fig.7. The horizontal axis is time and the vertical axis is the detected voltage. The signal reflected from bubble appears and the echo moves toward the sensor surface as the bubble goes up.

Then, UTDC velocity estimation was applied to the

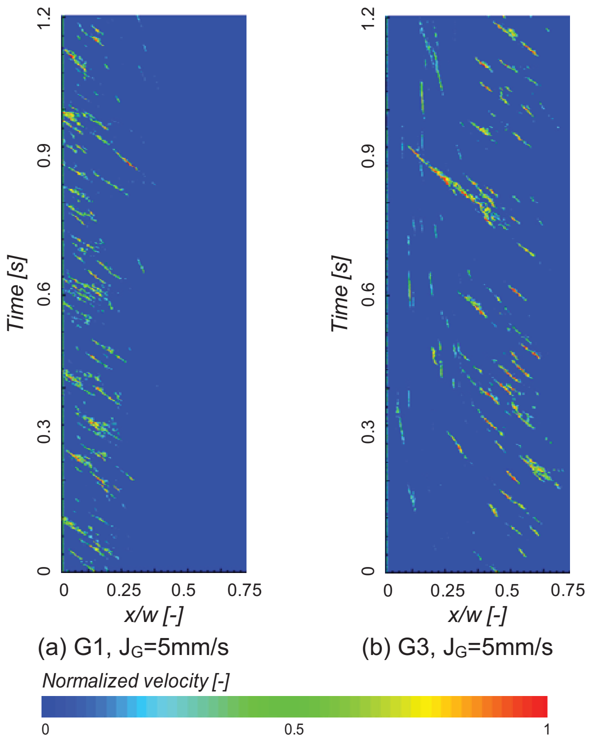


Figure8: Spatio-temporal bubble velocity distributions estimated by UTDC method from measured echo signals.

measured echo profiles, and the instantaneous bubble velocity profiles were obtained. The spatio-temporal distributions of estimated bubble velocity with 2MHz sensor are shown in Fig.8. The velocity normalized by the maximum velocity was represented by the color plot. Bubble velocities were measured when bubbles pass through the ultrasonic beam. The presence of bubble and passing frequency were found from these figures. The approximate size of bubbles may be estimated by the length of bubble trajectory. Comparing the gas inlet condition, bubbles flow near the wall in Fig.8 (a). On the other hand, there are many bubbles in the center of channel, as shown in Fig.8 (b). In addition, the dispersion of the bubbles is larger than gas inlet from G1.

The measured velocity profiles were averaged and illustrated in Fig.9. In the horizontal axis of this figure, 0mm means the wall of the flow channel and 50mm means the channel center. The profile shapes were changed by depending on the gas inlet condition with the same superficial velocity. However the relation between measured profiles, void distribution and ultrasonic transmission characteristics should be evaluated for high accurate measurement.

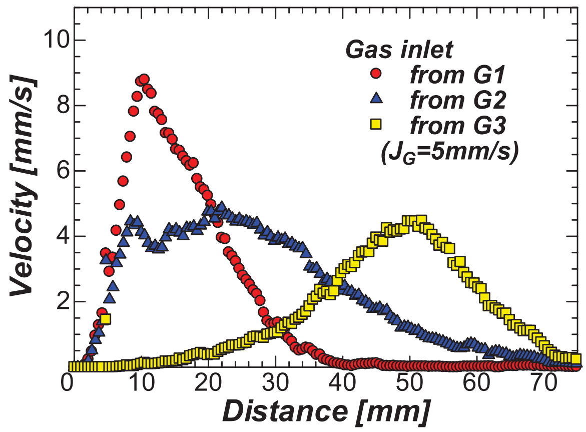


Figure 9: Averaged velocity profiles (averaging whole instantaneous velocity profiles).

5 SUMMARY

The applicability of the ultrasonic multi-wave sensors to air-water bubbly flow in the rectangular channel were investigated. The ultrasonic transmission characteristics of the sensor were investigated by experimental and numerical analysis and the effect on the measurement volume and ultrasonic beam formation, especially hollow effect, were evaluated. In air-water bubbly flow in a vertical rectangular channel, the reflected echo signals were measured using multi-wave sensor and the bubble velocity profiles are estimated by UTDC method. The effect of the ultrasonic beam characteristics should be clarified for the accurate ultrasonic velocity measurement.

REFERENCES

[1] Prasser H-M: A new electrode-mesh tomograph for gas-liquid flows, Flow Meas. Instrum. 9 (1998) 111-119.

[2] Ito D, Kikura H, Aritomi M, Prasser H-M: Bubble velocity estimation with three-layer wire-mesh sensor, ISFV13 (2008).

[3] Murakawa H, Kikura H, Aritomi M: Application of an ultrasonic array sensor to air-water bubby flow measurement, Flow Meas. Instrum. 19 (2008) 205-213.

[4] Yamanaka G, Kikura H, Aritomi M: Study on the development of novel velocity profiles measurement method using ultrasonic time-domain cross-correlation, Proc. ISUD3 (2002) 109-114.

[5] Ohtsuki S: Calculation method for the nearfield of a sound source with ring function, J. Acous. Soc. Japan, 30-2 (1974) 76-81.