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AIR-WATER BUBBLY FLOW MEASUREMENT USING ULTRASONIC MULTI-WAVE SENSORS

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ABSTRACT

An ultrasonic multi-wave sensor with more than two oscillators can measure the velocity profiles of both gas and liquid phase in bubbly flow by separating the reflected echo signals. In this study, two types of multi-wave sensors are used to measure air-water bubbly flow. The piezoelectric elements of a sensor have basic frequencies of 8 MHz for liquid phase and 2 MHz for gas phase, separately. On the other hand, another sensor has 8 MHz and 4 MHz elements in the transmitting face. These sensors have cylindrical shape. At first, to apply these sensors to flow measurement, the transmitted sound pressure fields were investigated by experimental and numerical approaches. Then, the echo signals reflected from air-water bubbly flow in a vertical rectangular channel were measured by using these multi-wave sensors, and the flow structures were estimated from statistical analysis of echo signals and ultrasonic velocity profiling method.

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 the flow and the heat transfer characteristics of the 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. Many investigations using especially a hotwire flow meter and a conductivity probe method [1] have been reported. In a transparent media, optical methods based on light transmission and photographical techniques have proved effectively, for examples laser Doppler anemometry and particle image velocimetry. In addition, the radiation system has been implemented for two-dimensional imaging of multi-phase flow [2]. However, since many real industrial systems demand non-intrusive, optically opaque, low cost and simpler to use, the above techniques are severely limited. Ultrasonic measurement has a possibility to fulfill these demands, and several major parameters can be obtained. So it is one of the successful measurements. Chang, et al. presented the void fraction measurement in bubbly flow by using the ultrasonic transmission technique, which is based on the propagation time of ultrasonic waves between two ultrasonic transducers [3]. On the other hand, the pulse-echo technique, which measure the signals reflected from the particles dispersed in fluid, is available to detect the flow regimes of two-phase flow [4]. Xu et al. developed the ultrasonic tomographic system, and they succeeded in identifying the flow regimes of gas-liquid two-phase flow and measuring the cross-sectional void fraction in horizontal tube [5].

NOMENCLATURE

c	[m/s]	Sound velocity
d	[mm]	Diameter
f	[MHz]	Ultrasonic wave frequency
J	[m/s]	Superficial velocity
t	[s]	Time
T	[°C]	Temperature
v	[m/s]	Velocity
V	[V]	Voltage
W	[m]	Width
x	[m]	Cartesian axis direction
y	[m]	Cartesian axis direction
z	[m]	Cartesian axis direction
Special characters		
ε	[-]	Void fraction
θ	[°]	Angle
λ	[mm]	Wave length
Subscripts		
bub		Bubble
in		Inside
out		Outside
G		Gas phase
L		Liquid phase

Velocity profile measurement is one of the most important factors in the flow structure clarification of gas-liquid two-phase flow. In the ultrasonic measurement, the velocity profiles can be obtained by the analysis of the pulse echo signals from the flow. Among the principal velocity profile measurement methods using pulse ultrasound are an ultrasonic Doppler method (UDM) [6] and an ultrasonic time-domain cross-correlation method (UTDC) [7]. The former can measure the velocity by detecting the ultrasonic doppler shift frequency of echo signals reflected from dispersed reflectors in fluid, and the latter can measure it by cross-correlating the consecutive echo signals. These two methods can perform the spatio-temporal measurements of the flow field, and have the possibility of clarifying the two-phase flow structure.

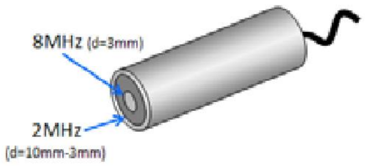
Aritomi, et al. applied the ultrasonic velocity profile measurement to air-water two-phase flow [8], and Suzuki, et al. developed a technique which can divide the measured velocity profiles into the gas phase and liquid phase velocities using the UDM [9]. In addition, using the separation technique, Murakawa, et al. measured the velocity profiles of air-water bubbly flow using a multi-wave transducer which can emit two ultrasonic beams with different frequencies [10,11]. The conventional ultrasonic measurements of two-phase flow have been applied only to air-water two-phase flow.

In this study, two types of multi-wave sensors are used for multi-wave ultrasonic velocity estimation in two-phase bubbly flow. The ultrasonic transmission characteristics of these 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 ultrasonic velocity estimation method.

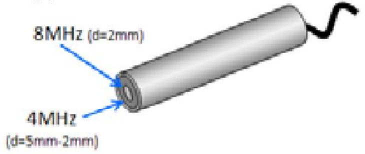
ULTRASOUND SOUND FIELD ANALYSIS

Two types of ultrasonic multi-wave sensors were applied to measure the flow. The multi-wave sensors have more than two elements in the sensor surface, as shown in Figure 1. 2/8MHz sensor has a circular element with 8MHz and a doughnut-shaped element with 2MHz. 4/8MHz sensor also has 8MHz element and 4MHz doughnut-shaped element. In these sensors, ultrasonic transmission characteristics from the elements with a hole are very important to measure flow measurement, because the measurement volume of ultrasonic beam affect the measuring accuracy. In this study, sound pressure field measurement is performed by the hydrophone technique and its numerical analysis is done by solving the Rayleigh equation with ring function [12].

In sound field measurement, the sound pressure field measuring system shown in Figure 2 was applied. This system consists of pulse transmitting devices (a pulser and an ultrasonic 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 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 3D stage is traversed in the test region and it receives the electrical signals with the



(a) 2/8MHz multi-wave sensor



(b) 4/8MHz multi-wave sensor

Figure 1 Schematics of ultrasonic multi-wave sensors

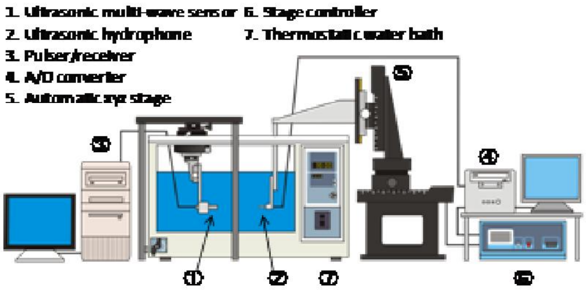
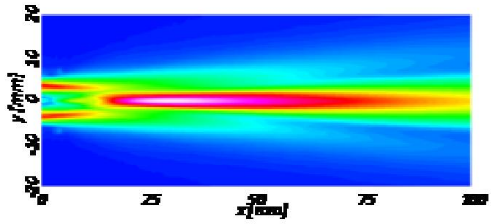
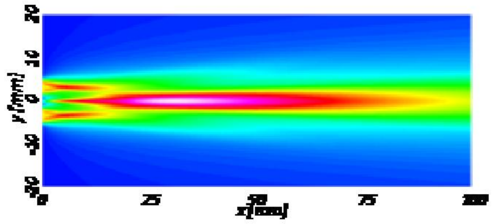


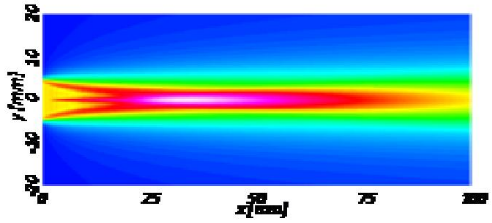
Figure 2 Three external boundary condition types



(a) Measured distribution

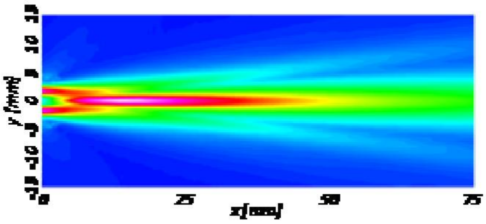


(b) Calculated distribution

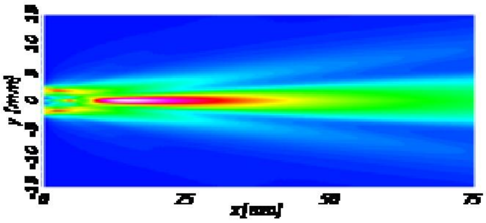


(c) Calculated distribution of normal 2MHz sensor

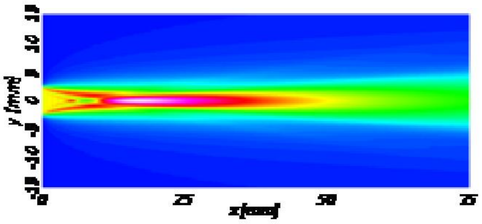
Figure 3 Comparison between experimental and numerical results (f=2MHz, D_{out}=10mm, D_{in}=3mm)



(a) Measured distribution

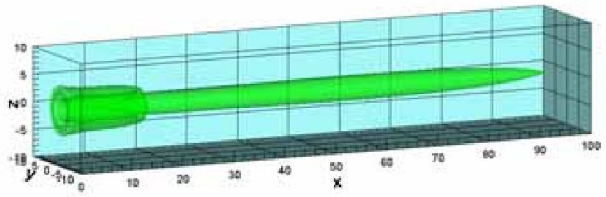


(b) Calculated distribution

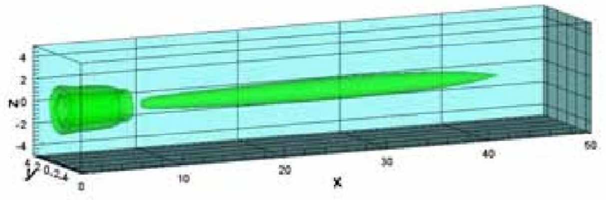


(c) Calculated distribution of normal 4MHz transducer

Figure 4 Comparison between experimental and numerical results (f=4MHz, D_{out}=5mm, D_{in}=2mm)

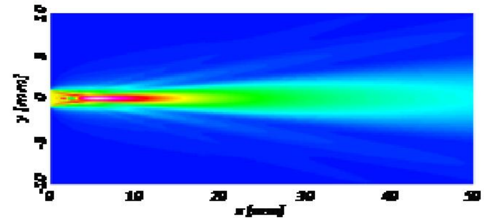


(a) Transmission from 2MHz element in 2/8MHz sensor

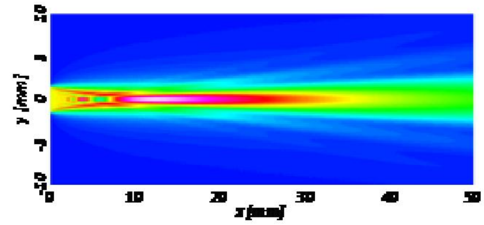


(b) Transmission from 4MHz element in 4/8MH sensor

Figure 5 3D sound field calculating results



(a) D = 2mm



(b) D = 3mm

Figure 6 Sound pressure distributions of 8MHz elements

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 is applicable to the transmitting path analysis of ultrasonic pulse in three-dimensional space. As sound field calculation, the ring function [12] was applied for the simplification of the calculation and reduction of computing time. The mesh size is the same as the measurement, and the mesh spacing is smaller than ultrasonic wave length (0.5mm for 2MHz, 0.2mm for 4MHz and 0.1mm for 8MHz). In the calculation, 3D beam formation can be estimated by extending the calculation region. The cycle per pulse of transmitted ultrasound is 2 for 2MHz, 4 for 4MHz and 8 for 8MHz, thus the pulse width is 1μs.

The sound pressure distributions measured and calculated were shown in Figure 3 and Figure 4. The color map represents the intensity normalized by the maximum value of detected voltage in the test area. Figure 3 (a) and (b), shows the results of ultrasonic sound pressure distributions in the case of the transmission from 2MHz element of 2/8MHz sensor. There are only a few differences between experiment and simulation. It shows that the weak area of ultrasonic intensity in the near region. The sound pressure attenuation attributed to the doughnut-shaped element of the sensor. Figure 3 (c) is a calculating result of normal 2MHz sensor with 10mm cylindrical element. It is clear that hollow effect comes from the element shape. On the other hand, Figure 4 shows the results of multi-wave 4MHz sensor. They also show the hollow effect due to the element shape. Because of the hydrophone size, the measured distribution is a bit rough. However the tendency of the beam is similar and the ideal field could be obtained by numerical way.

The 3D distributions of ultrasonic beam with iso-surface of -3dB of maximum pulse intensity are shown in Figure 5. The beam near the sensor (x=0~20mm for 2MHz sensor and x=0~8mm for 4MHz sensor) becomes bicylindrical shape. It is called "hollow effect". In these regions, it is difficult to define the measurement volume. However the beams after x=20mm for 2/8MHz sensor and x=8mm for 4/8MHz sensor are single cylindrical shape and with a nearly-constant diameter. Therefore, the ultrasonic beam without hollow effect should be used for the flow measurement.

The sound fields of 8MHz ultrasound were obtained numerically, because the element size of the hydrophone in the experiment is larger for 8MHz sensor which has 2 or 3mm diameter elements. Figure 6 shows the sound pressure

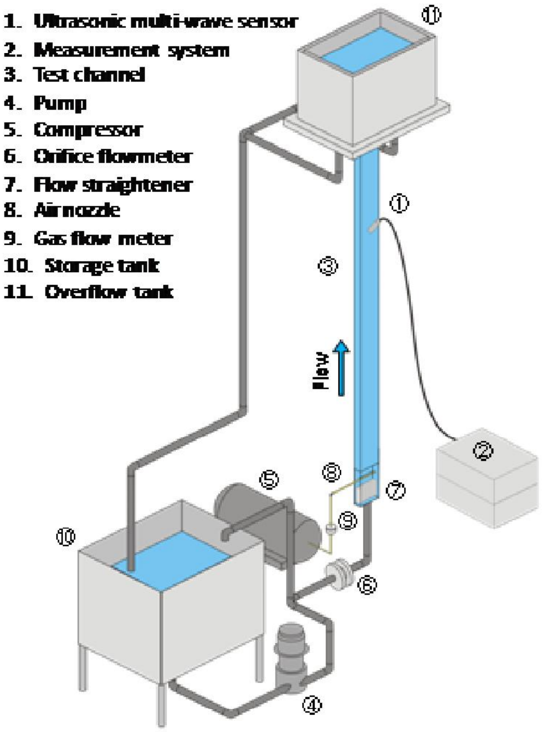


Figure 7 Experimental set-up

Table 1 Flow condition

Working fluid	Air, water
System pressure	Atmosphere
Superficial liquid velocity: J_L	0.1 m/s
Superficial gas velocity: J_G	5~20 mm/s
Temperature of water	20 °C

distributions with different diameter of element. In D=2mm, the beam attenuates from x=20mm, as shown in Figure 6 (a). So it can be applied only the measurement in near-field. In Figure 6 (b), the beam is longer and it has enough intensity for the flow measurement.

EXPERIMENTAL SET-UP AND METHOD

The experimental set-up consists of an air-water circulation system, a test channel section and a measurement system, as shown in Figure 7. The flow condition is shown in Table 1. Working fluids are air and water. Water flows into the test channel through a control valve, an orifice flow meter and a flow straightener (0.5mm 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 100mm downstream from the flow straightener. The outer diameter of each needle is 2mm and the diameter of holes drilled in each needle is 1mm. 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 total length of the test channel is 1,800 mm and the cross section is rectangular, 20×100mm^2, so the hydraulic equivalent diameter is about 33mm.

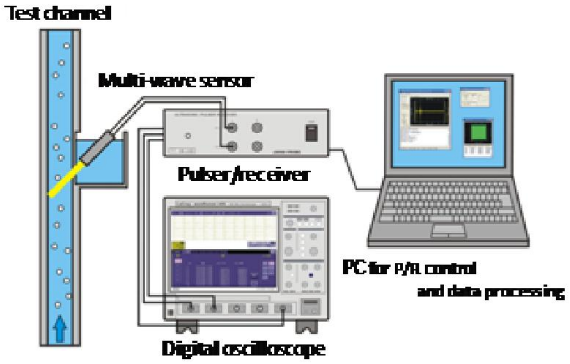
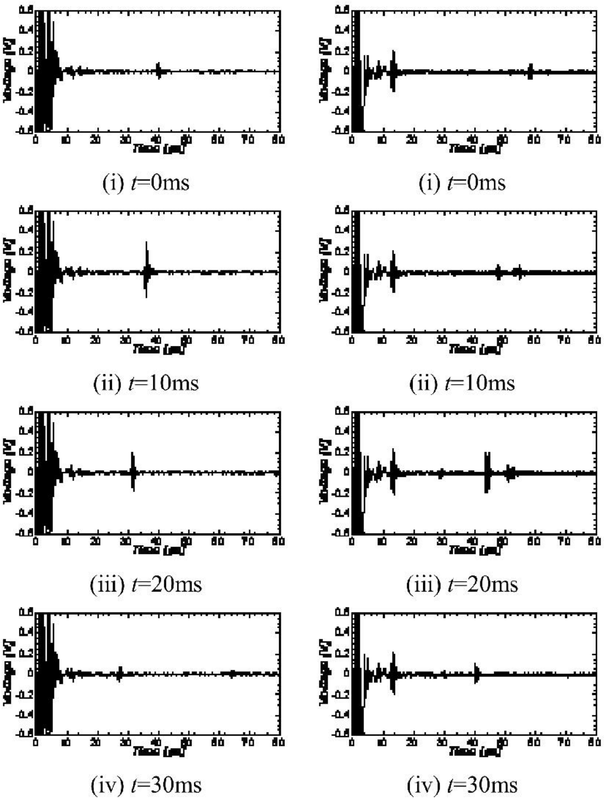


Figure 8 Ultrasonic multi-wave measurement system

Table 2 Specifications of ultrasonic multi-wave measurement

Pulse type	Burst wave
Pulse width	1.0 μs
Pulse repetition frequency	0.5 kHz
Sample rate	100MS/s (2MHz), 250MS/s (4MHz), 500MS/s (8MHz)
Vertical resolution	8 bit
Band width	400 MHz

The measuring section of 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 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). An ultrasonic multi-wave sensor was set up at 45 degrees in 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 reflection 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 and 4MHz sensor. The multi-wave measurement system is illustrated in Figure 8. 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. The specifications of multi-wave measurement are shown in Table 2. The sample rates were varied by the ultrasonic frequency because of the differences of wave length.



(i) t=0ms (i) t=0ms

(ii) t=10ms (ii) t=10ms

(iii) t=20ms (iii) t=20ms

(iv) t=30ms (iv) t=30ms

(a) 2MHz (b) 4MHz

Figure 9 Typical instantaneous echo signals reflected from bubbles (J_G=5mm/s)

RESULTS AND DISCUSSION

The ultrasonic multi-wave technique was applied to air-water bubbly flow measurement in a rectangular vertical channel. The reflected echo signals were recorded by the digital oscilloscope. Then the bubble velocity was estimated by UTDC method.

Echo signals of multi-wave sensors

The typical echo signals reflected from bubbly flows are shown in Figure 9. The horizontal axis is time and the vertical one is the detected voltage. They were measured by 2MHz and 4MHz sensors. The signal reflected from bubble appears and the echo moves toward the sensor surface as the bubble goes up.

The averaged echo intensity profiles along the ultrasonic beam are shown in Figure 10. In the horizontal axis of this figure, x/w=0 means the wall of the flow channel and x/w=0.5 means the channel center. The echo intensity was estimated from detected voltage, applied voltage and receiver gain [13]. There is a little difference of the echo intensity between 2MHz and 4MHz sensors, because the beam diameter of 4MHz sensor is less than that of 2MHz. In addition, the profiles show wall peak distribution of gas phase. As a previous study, they indicated that the bubbly flow becomes a wall peak at the same flow condition [14].

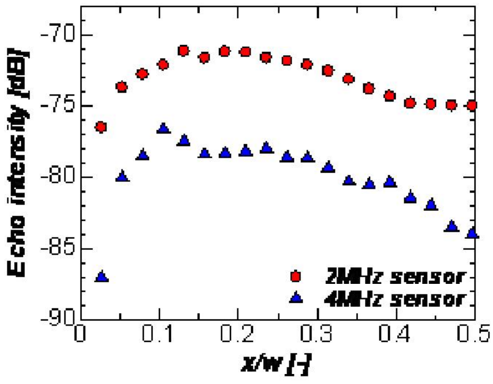
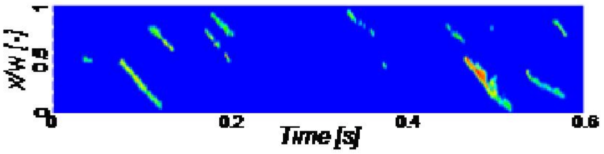
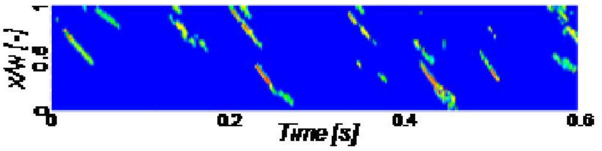


Figure 10 Averaged echo intensity profiles of 2MHz and 4MHz sensors (J_G=5mm/s)



(a) 2MHz

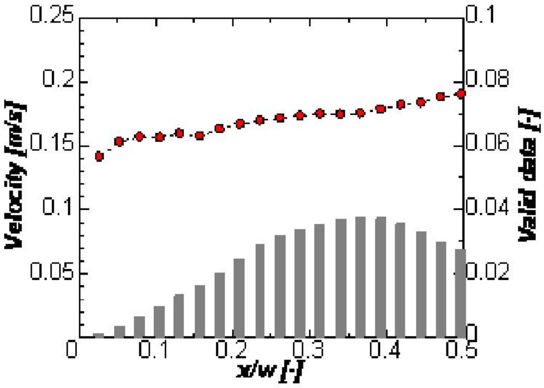


(b) 4MHz

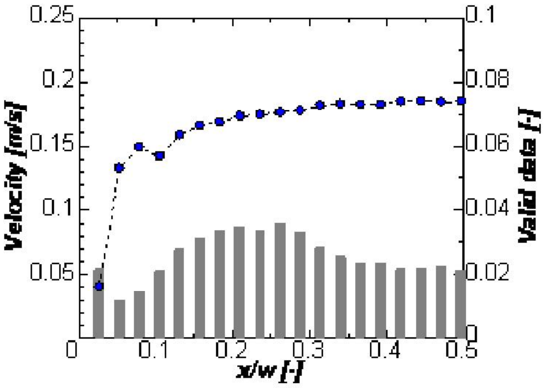
Figure 11 Spatio-temporal velocity distributions (J_G=5mm/s)

Estimation of bubble velocity profiles by UTDC

UTDC algorithm [7,11] was applied to the measured echo profiles, and the instantaneous bubble velocity profiles were obtained. The spatio-temporal distributions of estimated bubble velocity are shown in Figure 11. 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. Furthermore, the approximate size of bubbles may be estimated by the length of bubble trajectory. Figure 12 shows the averaged velocity profiles of bubbles. The velocities were corrected to the axial flow direction. The bubble velocity profiles could be measured by both 2MHz and 4MHz multi-wave sensors. However the effects of the beam formation in multi-wave sensor on the estimated velocity could not explain from these profiles. Therefore, it is necessary to compare between the ultrasonic beam characteristics and the measured velocity.



(a) 2MHz (50,000profiles)



(b) 4MHz (20,000profiles)

Figure 12 Averaged bubble velocity profile with 2/8MHz and 4/8MHz multi-wave sensors (J_G=5mm/s)

CONCLUSION

Two types of the ultrasonic multi-wave sensors were used to measured air-water bubbly flow in the rectangular channel. The ultrasonic transmission characteristics of these sensors 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 sensors 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.

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