Application of Ultrasonic Multi-wave Method for Two-phase Flow

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In order to obtain both liquid and liquid-gas interface velocities simultaneously, the authors developed a new measurement system referred to as multi-wave ultrasonic method. The measurement employs a unique ultrasonic transducer. In the present study, the characteristic of the multi-wave TDX was investigated. In order to apply the technique for flow measurement, incident angle of the TDX is one of the important parameter. Therefore, the ultrasonic intensity distributions at back of inclined acrylic plate and pipe are measured. From the results, appropriate incident angle and ultrasonic field for the measurements are obtained. Furthermore, the technique is applied to measuring bubbly and slug flows. Compared with the results of the multi-wave method and high-speed camera, it is confirmed that the technique can separate information of liquid and gas phases.

Keywords: multi-wave, ultrasonic intensity distribution, bubble, slug, cross-correlation, UTDC, UVP

1 INTRODUCTION

The authors had developed a unique ultrasonic transducer (TDX) referred to as multi-wave TDX. This TDX consists of two ultrasonic elements. Its use permits the emission of two types of ultrasonic wavelengths simultaneously and in the same positions. As an initial trial, measurements of bubbly flow in vertical pipes were carried out with the UDM-UDM measurement system [1]. The UDM-UDM measurement system ensured that both ultrasonic elements are connected to the UVP monitors. The velocity distributions of liquid and gas were then obtained. However, the flow conditions were too limited for this technique (mean Reynolds number: Re_m=8000, superficial gas velocity: J_G=0.00310). Hence, ultrasonic time-domain cross correlation (UTDC) method was applied to the multi-wave method for measuring bubble rising velocity in order to overcome the limitation [2]. Furthermore, the technique enabled to separate the liquid and gas velocity information. The rising velocities of the bubbles were obtained at 2 MHz of ultrasound and the liquid velocity distributions were obtained at 8 MHz by means of the UTDC.

In this study, the technique was applied to measuring both bubbly and slug flow. In order to compare the measured velocity and the interface position, high-speed camera was synchronized with the measurements.

2 MULTI-WAVE ULTRASONIC METHOD

2.1 Multi-wave Ultrasonic Transducer

Fig.1 shows a schematic diagram of the multi-wave TDX. A piezoelectric element of 8-MHz basic ultrasonic frequency with 3 mm diameter is installed in the center of the TDX. Furthermore, a piezoelectric element of 2-MHz basic ultrasonic frequency with hollow shape is set along the central axis. The inner diameter is 3 mm and the outer diameter is 10 mm. The each element is connected with BNC via lead wires. The piezoelectric elements are made of composite oscillator with PZT and plastic. An epoxy resin with half thickness of the wavelength λ is used as acoustic matching layer. Since the composite oscillator has low acoustic impedance, the energy loss is low at acrylic wall surface comparing with the other materials. Furthermore, the element has an advantage that is difficult to decrease the sensitivity. The multi-wave TDX emits ultrasonic beams independently for basic frequencies of 2 and 8 MHz, respectively. Using the multi-wave TDX, two types of ultrasonic beam diameter (D_{US}) can be obtained for multi-phase flow measurements using a single ultrasonic probe.

2.2 Measurement of Ultrasonic Intensity Distribution

The multi-wave TDX has a unique shape. Therefore, it is important to obtain the characteristics of the TDX, particularly for the 2-MHz ultrasound. Using a hydrophone method, measurement of ultrasonic pressure fields were carried out for the multi-wave TDX.

The measurement system consisted of automatic xyz-stage and a stage controller (Sigma Koki Co., Ltd.), a pulser/receiver (DPR300, JSR Co., Ltd.), an A/D board (PCI-5112, National Instrument Co., Ltd.), a PC and a water box. The A/D board was installed in a PC. The xyz-stage and the A/D board were controlled with the PC. An ultrasonic TDX was connected with the pulser/receiver. An ultrasonic

Figure 1: Schematic diagram of a multi-wave TDX.

hydrophone (NH8040, Toray techno Co., Ltd.) was traversed by the xyz-stage in order to measure the ultrasonic signal at each measuring point. The measurements were carried out in three dimensionally in order to prevent the inclination of the TDX. The signals were recorded at an A/D board, with a sampling rate of 100 MS/s. A maximum and minimum value was calculated from the 50 average ultrasonic signals. The peak-to-peak between the maximum and minimum of the signal was considered as the ultrasonic signal-intensity at the point. The minimum resolution of the measuring point was set at 0.5 mm. As the distance from the surface of the TDX, the resolution was increased from 0.5 to 5 mm in a longitudinal direction, from 0.5 to 2 mm in a radial direction. The total measuring point was 233 (radial plane) × 59 (longitudinal direction). The experiments were carried out in three conditions. The first condition was that the ultrasonic pressure distribution in water without any disturbance. The others were the pressure at back of an acrylic plate and pipe. The TDX was set at back of the pipe or plate with contact angle of 45° as shown in Fig. 2.

2.3 Characteristics of Multi-wave TDX

The results are shown in Fig. 3(a) and (b). Because of the intrusive between the TDX and the plate or pipe, it is impossible to measure the nearfield area. Therefore, the graphs start at 20 mm from the TDX surface. The gray-scale plots were normalized by the maximum value of the results without any plate. Therefore, the gray-scale represents the relative intensity in between the no-plate condition and pipe-condition. In each measurement condition, there are not any differences between them except the maximum intensity of ultrasonic. With setting the acrylic plate or pipe, the ultrasonic intensity weakens. However, it is not observed that the ultrasonic bend or wider because of the plate/pipe effect. Based on the results of maximum intensity in each condition, the intensity of the ultrasonic with 8-MHz wavelength weakens if it passes the acrylic plate or pipe. The decreases of the intensity are larger than the results of 2 MHz. Therefore, the 8-MHz basic frequency is strongly affected by the wall material where the TDX is set more than the 2-MHz frequency.

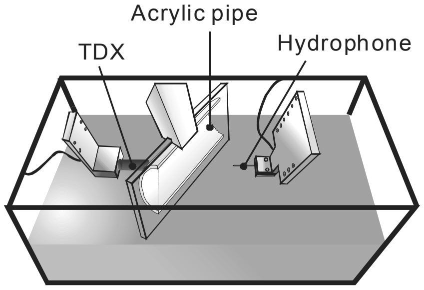


Figure 2: Schematic diagram of a experimental apparatus of ultrasonic intensity distributions at back of an acrylic pipe.

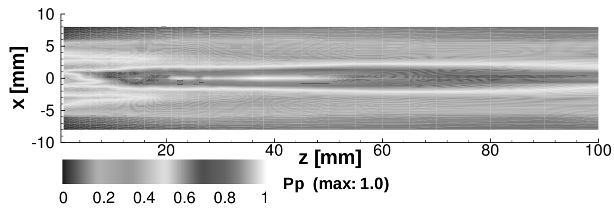
From the above investigations, it is found that the multi-wave TDX can be used for measuring bubbly flow. Furthermore, the difference of measurement volume in each frequency is confirmed. Therefore, characteristic of the ultrasound based on the measurement volume is expected.

3 EXPERIMENTAL FACILITIES AND SIGNAL SETTING

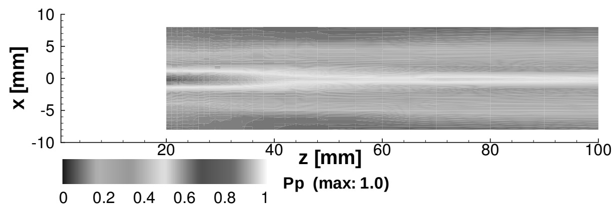
3.1 Experimental Apparatus

The measurement system includes two ultrasonic pulsers/receivers (DPR35+, JSR Co., Ltd. and TB-1000, Matec) in order to emit and receive ultrasonic pulses. Both 2-MHz and 8-MHz ultrasonic elements were connected to the pulsers/receivers. The echo signals received in each pulser/receiver were recorded on an A/D board (PCI-5112, National Instrument Co., Ltd.), with a sampling resolution of 8 bit and a sampling rate of 100 MS/s at two channels. The A/D board was installed in a PC. The A/D board and the pulsers/receivers were connected to each other and synchronized. Therefore, both the 2-MHz and 8-MHz ultrasonic echo signals were simultaneously recorded. The recorded data were calculated by the PC using the correlation method and the velocities were obtained. The signal acquisitions and calculations were simultaneously carried out.

In each channel, 101 consecutive signals were recorded continuously at a sampling rate of 1,000 Hz. The sampling rate and spatial resolution are related to each other. It is well known that the sound velocity in water at 19.5 °C is 1,480 m/s. Therefore, the channel width, which represents the spatial resolution, was set at 0.74 mm. When the sampling rate is set at 100 MS/s, the number of acquisition data in each channel is 100. The velocity resolution, maximum velocity along the TDX, and search



(a) Without any plate



(b) At back of an acrylic pipe

Figure 3: Measurement results of ultrasonic intensity distributions in 2 MHz of multi-wave TDX.

window for the UTDC calculation are related to each parameter. Therefore, the maximum velocity was set as 0.74 m/s, and the velocity resolution was set at 100 divisions of the maximum velocity. The measurement test section was vertical pipe with an inner diameter of 50 mm. The multi-wave TDX was installed on the outer surface with a contact angle of 45°. The measurements were conducted at downstream at a distance of 67*D* from a bubble generator.

Based on the above setting, 100 velocity distributions were calculated for acquiring 101 continuous echo signals. In these experiments, the acquisitions of the signals were repeated 100 times. A total of 10,000 velocity distributions were obtained.

3.2 Signal Setting

Since the echo signals of the ultrasonic beam reflected by the bubbles are stronger than those reflected by particles, the particles signals can be easily eliminated from the recorded data at an ultrasonic wavelength of 2 MHz. Therefore, the bubble-rising velocity distributions are easily obtained. However, the bubble data must be eliminated from the measured data at 8 MHz in order to calculate the liquid velocity distribution. If the signal at 8 MHz includes echo signals reflected by the bubble, the signal can be recorded at 2 MHz as well. Based on this concept, it is possible to obtain only liquid data using an 8-MHz signal.

Fig. 4 shows a schematic diagram of the measurement of the two-phase bubbly flow using a multi-wave TDX. Ultrasonic measuring volumes of 2-MHz and 8-MHz signals are overlapped in the test section. If the echo signals reflected by the particles are eliminated from the measured signals of a 2-MHz beam, the bubble and particle positions can be divided into three patterns. Based on the presence of the particles and bubbles, a combination of the echo signals at 2 MHz and 8 MHz can be divided into 3 groups. These combinations are as follows: Pattern A—echo signals appear at 2 MHz and no echo signal appear at 8 MHz; Pattern B—echo signals appear at both ultrasonic wavelengths; Pattern C—no echo signal at 2 MHz and echo signals appear at 8 MHz. Based on the signal setting, the bubble and liquid velocity distributions can be divided. Bubble-rising velocities are obtained using the echo signals recorded at 2 MHz that yield Pattern A and B. On the other hand, by subtracting the data for Pattern B from the recorded signals at 8 MHz, liquid velocity distributions are obtained.

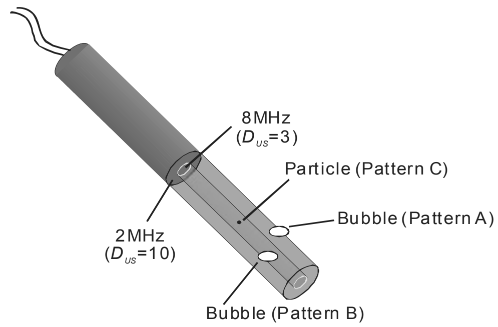
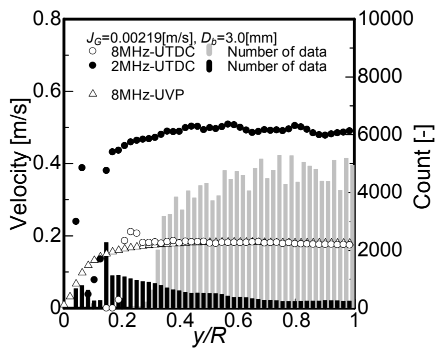


Figure 4: Schematic diagram of two-phase flow measurement using the multi-wave TDX.

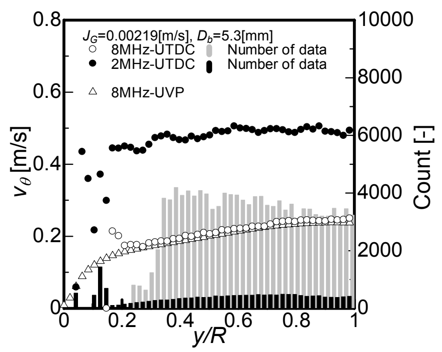
4 EXPERIMENTAL RESULTS

4.1 Measurement of Bubbly Flow

Figs. 5 show the measurement results at J_G=0.00219 m/s and Re_m=8,000. The results of the liquid velocity distribution are compared with the data measured using the UVP monitor. The circles represent the distributions measured using the UTDC. The black and gray bars represent the data of the 2-MHz and 8-MHz ultrasonic wavelengths measured in each channel position. It can be clearly seen that the data distributions are affected by the void-fraction distributions. When the void fraction is small, the data of the bubble-rising velocity is extremely low. Since the data was not sufficient for calculating the bubble-rising velocity, the time average gas velocity distribution fluctuates. On the other hand, the data for the liquid velocity is sufficient for the calculation. Since smaller bubbles tended to rise near the wall region, the data acquisition of bubbles the near wall region is larger than that in other areas. On the contrary, the number of data of the liquid is larger when *y*/*R* > 0.3. In general, the calculation of the liquid velocity



(a) D_b=3.0mm: wall-peak condition



(b) D_b=5.3mm: core-peak condition

Figure 5: Average liquid and interface velocity distributions in bubbly flow.

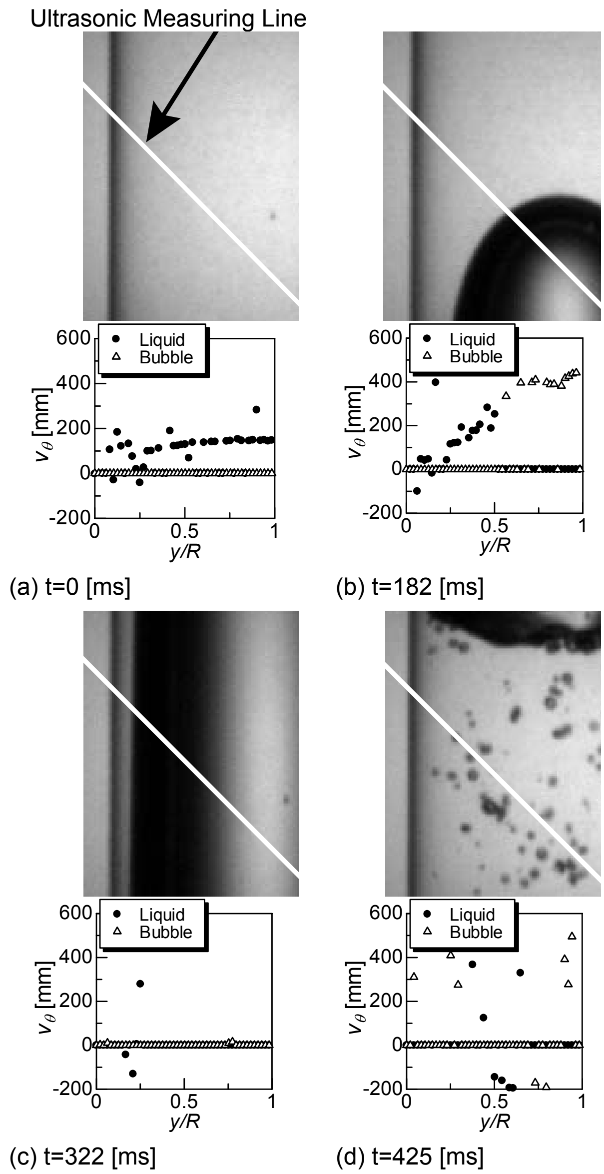


Figure 6: Pictures and velocity distributions of slug flow by using ultrasonic and high-speed camera.

distribution is more difficult than that of the bubble-rising velocity because the echo signals reflected by the particles have less intensity. However, the results of the velocity distributions are in good agreement with that measured using a UVP monitor. The liquid velocity distribution has a larger error particularly near the wall region. This is because some liquid data include the bubble-rising velocity. Furthermore, data on the liquid velocity around the region is insufficient. This implies that the bubble data could not be completely eliminated from the data measured by using the 8-MHz ultrasonic wavelength. It is confirmed that the bubble-rising velocity data varies and that it is larger near the wall region. This is an effect of the beams overlapping the area between the wall region and the ultrasonic measuring volume. D_{US} of the 2-MHz ultrasonic wavelength is comparatively large. The wider region overlaps with the wall of the test section.

4.2 Measurement of Slug Flow

The results of measuring slug flow are shown in Fig. 6. Simultaneous measurements with high-speed camera and ultrasonic were carried out, in order to synchronize the picture and the measured velocity. The figures represent the rising process of a slug bubble under the condition of Re_m=4,000.

When the time (*t*) is 0, the liquid velocity distribution was obtained by the data of 8-MHz ultrasonic wavelengths. When the slug bubble crosses the ultrasonic measuring line, the liquid velocity is accelerated by the bubble motion. The time resolution obtaining a velocity distribution was set at 1 ms, which is higher than that of UVP. Therefore, the motion of slug bubble could be obtained by using both the ultrasonic and high-speed camera. The interfacial velocity is obtained by the 2-MHz ultrasonic wavelength at *t*=182ms. Furthermore, both velocities distributions are completely distinguished. When the bubble rises the ultrasonic measuring line, ultrasonic cannot penetrate the gas phase. Therefore, only the liquid film velocity was obtained. However, the calculation of the cross-correlation has relatively large error, in particular, near wall region. The result might include the error velocity. After the bubble passes the measuring line, complex velocity distributions appear, because the leading bubble induce the wake turbulence. In order to evaluate the accuracy of the measurement, further improvement of the technique is necessary.

5 SUMMARY

The multi-wave method was applied for two-phase flows, *i.e.* bubbly and slug. The developed phase separation technique can detect the liquid-gas interface at a slug bubble. The main advantage of this method is that it enables the simultaneous acquisition of two target velocity distributions at the same position. For further improvement in the measurement accuracy, this method can be applied for the clarifications of the flow structure in the wake region behind a slug bubble, interaction mechanism between the liquid and bubble, and monitoring of a bioreactor.

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