APPLICATION OF MULTI-WAVE TDX FOR MULTI-PHASE FLOW MEASUREMENT

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ABSTRACT

This paper proposes a new measurement technique for multi-phase flow. To measure two kinds of phases at the same place and the time, Multi-wave TDX was newly developed. This TDX includes the two different ultrasonic elements. At first, this TDX was applied for ultrasonic Doppler method (UDM). As changing of the measuring volume of the ultrasonic, the measured data using the UDM change. Applying the effects of measuring volume, the liquid velocity and the bubbles' rising velocity are obtained using the UDM in two-phase bubbly flow. Furthermore, applying ultrasound correlation method (UTDC) for the Multi-wave TDX, the bubbles' rising velocity can be obtained at more accurately. With emitting two kinds of ultrasonic at the same time, two different signals can be obtained. Comparing with the each signal, the bubbles' velocity information can be eliminated from the other signal. Using the UTDC and the signal comparison method, the velocity distribution can be obtained at the same time and the position. This method does not need the velocity difference between two objects, such as the bubbles and the liquid. Hence, this method can be applied for other multi-phase flow.

Keywords: Multi-wave TDX, UDM, UTDC, and Multi-phase flow

INTRODUCTION

This paper proposes a new measurement technique for multi-phase flow using Multi-wave TDX and ultrasonic method.

Zhou *et al*. [1] developed a system to measure the velocity fields in bubbly flows by means of ultrasonic Doppler method (UDM). When the UDM is applied to two-phase bubbly flow, ultrasonic pulses are reflected on both seeding micro-particles in liquid-phase and gas-liquid interfaces. Hence, the velocity data measured by the UVP monitor will include velocity information of both phases.

To apply the statistical method to the UDM, the relation between flow condition and ultrasonic beam diameter is an important factor. With the increase of void fraction, the possibility of bubbles' crossing the measuring line increases. Furthermore, the relation between bubbles' size and TDX's beam diameter is important as well. On the other hand, if an adequate diameter of TDX is applied for multi-phase flow, each phase velocity can be measured using these relations.

To measure liquid velocity distribution at higher sampling frequency and better spatial resolution, ultrasound correlation method (UTDC) was developed [2]. This method is based on cross-correlation between two consecutive echoes of ultrasonic pulses to detect the velocity. Yamanaka *et al.* [3] tried to apply this method for two-phase bubbly flow measurement.

In this paper, a new measurement method for multi-phase flow is proposed using the Multi-wave TDX and ultrasonic methods. The Multi-wave TDX is composed of two different ultrasonic elements and can emit two kinds of ultrasonic independently. This new method employs several kinds of particles whose sizes are greatly different. For each particle, if the TDX of an appropriate size can be selected, the measured velocity PDF mainly includes a particles' velocity suitable for the TDX's diameter. As the measurement volume changes, the majority of the recorded velocity also changes for each particles size. At first, measurements of bubbly flow using the UDM and the Multi-wave TDX are conducted. Using these methods, the bubbles' rising velocity and liquid velocity distributions are obtained at the same time. Furthermore, to clarify the accuracy of the measuring multi-phase flow, ultrasound time-domain correlation method is applied.

EFFECT OF MEASUREMENT VOLUME

Measurement system of the UDM consists of Ultrasonic Velocity Profiles monitor (UVP-monitor) and TDX. Ultrasonic pulses reflect on liquid-gas interfaces, so the measured velocity profiles must be divided into gas and liquid velocity information. By adopting the UDM to bubbly-flow measurements, the liquid velocity information can be calculated using statistical method [4]. The first step in dividing the velocity information is to obtain the probability density function (PDF) of all measured instantaneous velocities at each measuring position. Bubbles rising velocity is faster than liquid velocity in the case of upward bubbly-flow. Hence, an instantaneous velocity profile has a typical peak if a bubble crosses the measuring line.

Fig. 1 shows an example of velocity PDF at a channel position for each TDX [5]. The velocity was measured in co-current upward bubbly flow in a rectangular channel (20 x 100 mm^2). Because the bubble rising velocity is higher than the liquid velocity, the velocity PDF of the bubbles is higher than that of the liquid at each channel. As a result, velocity PDF can

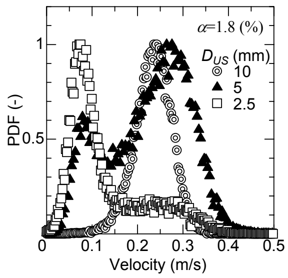


Fig. 1 Velocity PDF depending on the measuring volume [5]

Fig. 2 Multi-wave TDX

be calculated as shown Fig. 1. The probability of bubbles' crossing the measuring line becomes higher with the increase of TDX's diameter (D_{us}). At D_{us}=2.5mm, the velocity PDF has a peak value at the mean liquid velocity. However, at the condition of D_{us}=5mm, the maximum value of the PDF becomes higher to the velocity around bubbles' rising velocity and has two peaks. Furthermore, the PDF has one maximum and peak value at D_{us}=10mm. If the void fraction (α) becomes low, these PDF also change. Taking into account these characteristics, TDX must be selected as related to the relative diameters between bubbles and D_{us}, and void fraction. The bubble diameter of this condition was about 3-4mm and void fraction was 1.8%. From these results, about D_{us}=2.5mm must be selected to measure the liquid velocity under this condition. On the other hand, about D_{us}=10mm, the measured data mainly include the bubble rising velocity. This is the reason why that if the D_{us} increases, ultrasonic reflection on the particle relatively decreases for its element diameter.

MULTI-WAVE TDX

The attempt to measure the velocity of each phase was performed by changing the TDX's diameter. From the result shown in Fig.1, D_{us}=10mm and 3mm were selected to measure the bubble and liquid velocity, respectively.

To emit different sizes of ultrasonic beam at the same time and the same position, the Multi-wave TDX is newly developed (Fig. 2). The new TDX consists of special ultrasonic element. The ultrasonic element has two basic frequencies. The central 3mm-diameter area has 8MHz basic frequency and the outer area has 2MHz frequency. Generally, the size of element corresponds to its basic frequency. The Multi-wave TDX can emit ultrasonic independently for 2MHz and 8MHz basic frequencies.

UDM MEASUREMENTS AND METHOD

In this study, two kinds of experiments were performed using the Multi-wave TDX. First experiments were measuring two-phase flow using the UDM. Changing of the ultrasonic measurement volume, the velocity probability density function (PDF) also changes. Using the property, both of the bubbles' rising velocity and the liquid including nylon tracer particles were measured. The 2MHz(ϕ10) ultrasonic pulses mainly reflected on the liquid-gas interfaces. Because the ultrasonic

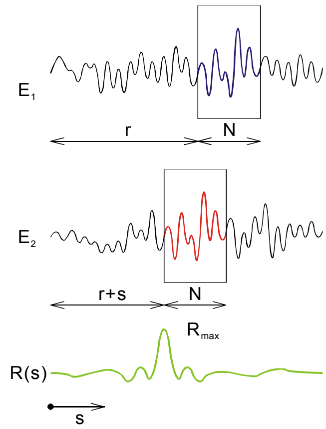


Fig. 3 Concept of the UTDC [2]

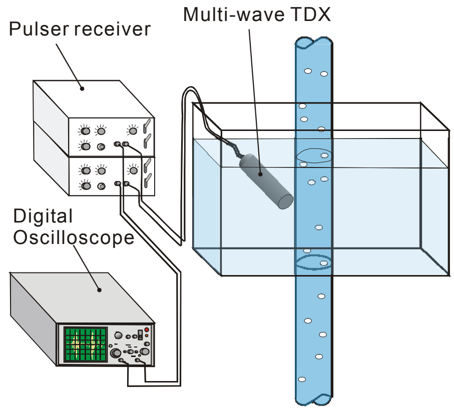


Fig. 4 UTDC system using the Multi-wave TDX

pulses strongly reflect at the bubbles' surface, and the possibility of bubbles' crossing the measuring line becomes high. Furthermore, the 2MHz ultrasonic element of Multi-wave TDX is more difficult to detect particles comparing with normal 2MHz TDX because of its central holes, i.e. 8MHz element. On the other hand, the 8MHz(ϕ10) ultrasonic element can easily receive the ultrasonic pulses reflected on both of the particle and the liquid–gas interfaces.

The velocity distributions were measured using X-3 PS-I model UVP monitor (Met Flow AG). The velocity PDFs were calculated from measured data at the two-phase bubbly flow. The 2MHz ultrasonic element is larger than that of 8MHz. Hence, the measured data mainly include the bubbles' rising velocity. However, the measured data using the 8MHz element includes both of the liquid including tracer particles and bubbles' rising velocity even if the condition is constant. From the velocity PDF, the time-averaged velocity is calculated from 2MHz data. On the other hand, the measured data using 8MHz ultrasonic element include both of the liquid and bubbles' rising velocity information. From these data, the bubbles' rising velocities were eliminated from all of the measured data using statistical methods [4]. From these calculation methods, the time-averaged velocity distributions for liquid and gas are calculated using the Multi-wave TDX.

UTDC MEASUREMENTS

The UTDC is based on cross-correlation between two consecutive echoes of ultrasonic pulses to detect the velocity (Fig. 3). In this study, the UTDC was applied for bubbly flow measurement. Using a normal TDX, the separation techniques between the liquid and gas velocity information are very

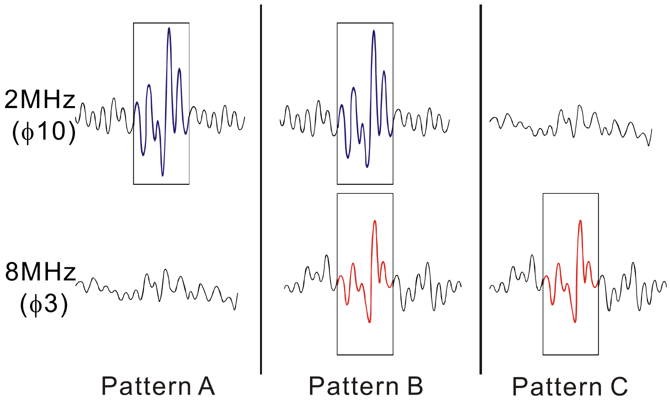


Fig. 5 Signal patterns of the UTDC

difficult. For this reason, the Multi-wave TDX was used for measuring of two-phase bubbly flow. Fig. 4 shows the schematic of the UTDC. The each element of the Multi-wave TDX was connected with each pulser-receiver (DPR300 and DPR35+, JSR Co. Ltd.) respectively. Hence, the ultrasonic pulses and their echo signals were received independently by a digital oscilloscope (LC-574A, Lecroy Co. Ltd.). The pulses were triggered with each pulser-receiver and the digital oscilloscope. The digital oscilloscope has the 8-bit A/D converter. The each signal can be recorded at a sampling of 100MS/s. The echo signals can be compared with the 8MHz and 2MHz at the same time using the system. The 2MHz echo signal was adjusted to detect only the bubbles. On the other hand, the 8MHz signal was adjusted to detect both the particles and bubbles. It was confirmed that the signal of 2MHz could not detect the particles in this adjustment.

Signal processing

The digital oscilloscope can record both the 2MHz and 8Mhz echo signals. Comparing with each signals at the same time and same position, the authors tried to divide into three patterns as shown in Fig. 5.

Pattern A : 2MHz signal include reflected pulse
8MHz signal not include reflected pulse

In the case of Pattern A, the pulse reflected on a bubble. Because the measurement volume of 2MHz is larger than that of 8MHz. Hence, the bubble is estimated to cross the only 2MHz measuring line.

Pattern B : 2MHz and 8MHz signal include reflected pulse

In the case of Pattern B, the signal is apparently reflected pulse on a bubble's surface.

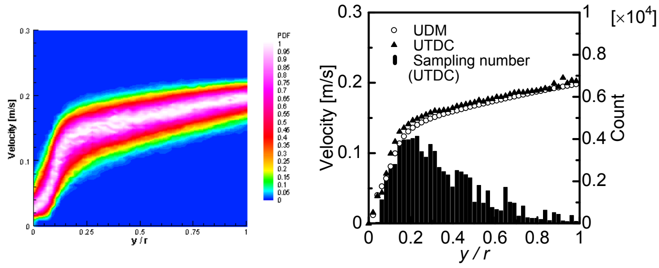
Pattern C : 2MHz signal include reflected pulse
8MHz signal not include reflected pulse

In this case, the signal pattern is opposite to Pattern A. The signal can be regard as the particle reflection, because the 2MHz ultrasonic was adjusted as not to detect the particles.

RESULTS AND DISCUSSION

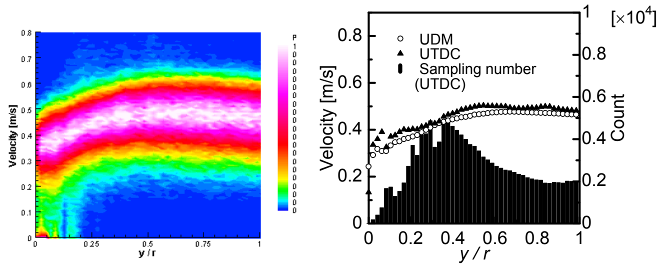
All of the experiments were performed at vertical pipe (i.d.=50mm) and z/d=23 from a bubble generator. The experimental condition was set at constant values of mean Re_m=8000, superficial liquid velocity J_G=0.00310m/s.

To compare the UDM and the UTDC, a measurement of single-phase flow was conducted. Fig. 6(a) shows the color



(a) Velocity PDF (UDM) (b) Velocity distribution (UDM vs. UTDC)

Fig. 6 Liquid velocity distribution (single-phase flow)



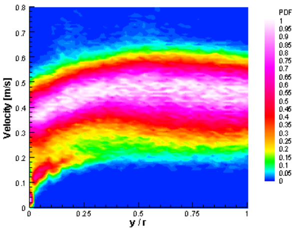
(a) Velocity PDF (UDM) (b) Velocity distribution (UDM vs. UTDC)

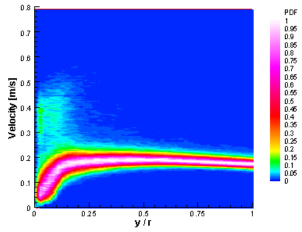
Fig. 7 Bubbles' rising velocity distribution (two-phase flow)

map of velocity PDF for each position measured using the UVP monitor. From the velocity PDF, time-averaged velocity distribution using the UDM is calculated as shown in Fig. 6(b). Furthermore, the UTDC measurement was performed at the same condition. Comparing with each other, the velocity distributions are almost the same. However, error of the velocity increases with increase of the distance from the wall because of the signal intensity decreasing. Furthermore, to compare the bubbles' rising velocity distribution, bubbles' velocity were measured (Fig. 7). In this condition, there were few particles in the liquid. Hence, the velocity data measured using the UDM mainly include the bubbles' rising velocity. The reason there are small differences between the results might be the effect of the small number of the including particles.

Two-phase flow measurement

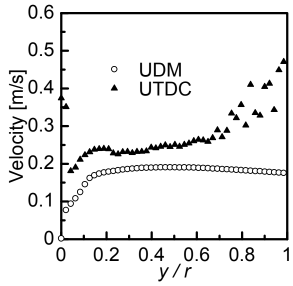
To obtain the bubbles' rising velocity and liquid velocity in two-phase bubbly flow simultaneously, the UDM were conducted using the Multi-wave TDX. The measured velocity PDFs using each element at the same condition were shown in Fig. 8. From these color maps, it can be clarified that the possibility of measuring the bubbles' rising velocity is strongly different. In the case of the 2MHz ultrasonic element, the bubbles' velocity information is dominant. On the other hand, it is clarified that the many of bubbles rise at the near wall region from the data measured using the 8MHz element. From these velocity PDFs, the bubbles' rising velocity and liquid velocity distributions are calculated. The measured data by the 2MHz element is considered as the bubbles' rising velocity distribution because the ratio of measured particles is too small. On the other hands, the raw data measured using 8MHz-element include both of the liquid and gas velocity. Hence, the bubbles' rising velocity information was eliminated from all of the data [4].



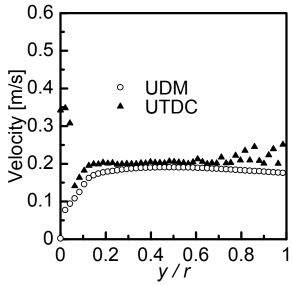


(a) 2MHz element (ϕ10) (b) 8MHz element (ϕ3)

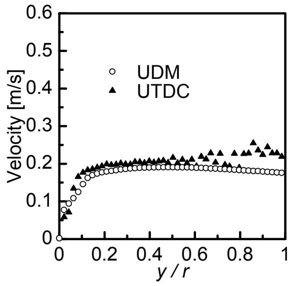
Fig. 8 Velocity PDF in two-phase bubbly flow



(a) No elimination from the UTDC raw data



(b) Considering of the velocity difference



(c) Signal comparison method between 2MHz and 8MHz

Fig. 9 Liquid velocity distribution
(8MHz, UDM vs. UTDC)

Liquid velocity distribution measured using UTDC

Fig. 9(a)-(c) show the liquid velocity distribution measured using UTDC and 8MHz ultrasonic element as changing of the data processing. The 8MHz ultrasonic reflect on the both of the particles and the liquid-gas interface. Hence, calculated date by the UTDC includes the liquid and gas velocity information. Fig. 9(a) shows the ensemble averaged velocity distribution by all of the UTDC data. This data is apparent different from the UDM measured data. To eliminate the bubbles' rising velocity, following two methods were adopted.

As same as the UDM data processing, the information of the velocity difference between the liquid and the bubbles are considered to calculate the liquid velocity. If the velocity is higher than the threshold velocity, the data regarded as the bubble's velocity. Following the process, the liquid velocity distribution was calculated as shown in Fig. 9(b) using UTDC. The velocity distribution is almost the same with the data measured using UDM. However, this method is limited to adaptability for multi-phase flow, i.e. the two objectives must have different velocity.

To eliminate the bubbles' information, signal comparison method was applied for the 2MHz and 8MHz ultrasonic signals. 8MHz ultrasonic signals include the Pattern B and Pattern C (Fig. 5). From the 8MHz signals, comparing with 2MHz and 8MHz signals, the Pattern B signals are eliminated. Using the Pattern C data, the velocity distribution was calculated as shown in Fig. 9(c).

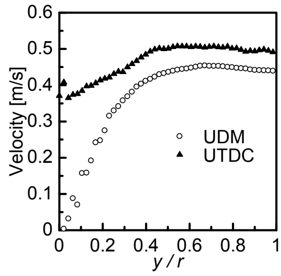


Fig. 10 Bubbles' rising velocity distribution
(2MHz, UDM vs. UTDC)

Bubbles' rising velocity distribution

Fig. 10 shows the bubbles' rising velocity measured using UTDC and UDM at 2MHz ultrasonic. Comparing the measured data, the UDM velocity data is smaller than that of the UTDC. Taking into account the results of Fig. 1 and Fig. 7(b), existence of tracer particles decrease the bubbles' rising velocity. This is why the UVP monitor measures the volume-averaged velocity. Hence, with decrease of the ratio of the particles, the bubbles' rising velocity distribution becomes the same values with the result of the UTDC.

CONCLUSIONS

New measurement technique for multi-phase flow using the Multi-wave TDX is proposed. This method can be applied for the both of the UDM and the UTDC. Using the UDM, the liquid velocity distribution can be easily obtained. Furthermore, it is shown that the possibility of measuring several phases simultaneously using the UTDC and the Multi-wave TDX.

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