Identification of liquid-gas interface based on ultrasonic reflected signal for two-phase flow velocity measurement

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When an ultrasonic velocity profile (UVP) method is applied to two-phase flow measurements, ultrasonic pulses are reflected on both the seeded micro-particles in liquid phase and the gas-liquid interfaces. Hence, the velocity data measured by the UVP method includes velocity information of both phases. Therefore, the phase separation has been a long out standing problem. In order to analyze the reflected signal, UVP system was developed by using a pulser/receiver and a digitizer. The method can select two velocity calculation algorithms that are the Ultrasonic Doppler Method (UDM) and the Ultrasonic Time-domain Cross-correlation method (UTDC). Synchronizing measurement with a high-speed camera and the UDM was established, and measured two-phase flow in a horizontal duct at 2 ms interval. Furthermore, signal analysis of the reflected on liquid-gas and liquid-particles interfaces were conducted. The phase change based on the acoustic impedance. Based on the property, it was found that it was possibly to distinguish between liquid-gas interfaces and micro-particles in liquid phase.

Keywords: UVP, UDM, UTDC, two-phase flow, gas-liquid interface, identification method

1 INTRODUCTION

Two-phase flow has been investigated over the past several decades. However, due to its complexity, some characteristics of the phenomena have not yet been thoroughly understood such as turbulent phenomena, bubbles' motion, and so on. The velocity of rising bubbles is an important parameter to obtain both void fraction and drift velocity in two-phase flow. For understanding the two-phase flow, ultrasonic measurement technique is a powerful tool to obtain the flow parameters. The technique has several desirable characteristics; it is non-intrusive and is applicable to existing pipes. When the ultrasonic velocity profile (UVP) method is applied to the two-phase flow measurements, ultrasonic pulses are reflected on both the seeded micro-particles in liquid phase and the gas-liquid interfaces. Hence, the velocity data measured by the UVP method includes velocity information of both phases. Therefore, the phase separation has been a long out standing problem. Suzuki et al. [1] applied a statistical method based on the velocity different between liquid and bubbles in a vertical duct for measuring the liquid velocity distributions around a bubble. For the other approach, signal intensity method using two ultrasonic frequencies was developed for measuring liquid and bubble velocity distributions individually [2,3]. Velocity analysis is applied for detecting liquid-gas interface measured by a commercial system of UVP [4]. These methods mainly calculated from the obtained velocity profiles.

In order to analyze the reflected signal, ultrasonic velocity profile system was developed. The method can select two velocity calculation algorithms that are the ultrasonic Doppler method (UDM) and the ultrasonic time-domain cross-correlation method (UTDC) [5]. At first, the system was evaluated by measuring single-phase flow. Furthermore, a synchronizing measurement with a high-speed camera and the UDM was established, and measured two-phase flow in a horizontal duct at 2 ms interval. Furthermore, signal analysis of reflected on liquid-gas and liquid-particles interfaces were conducted.

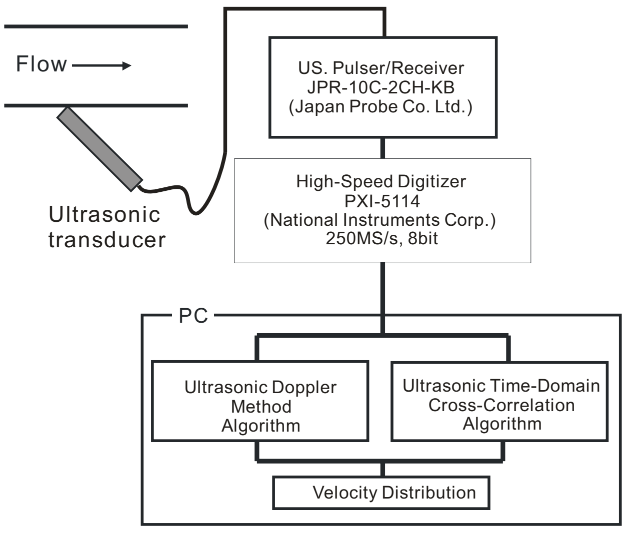


Figure 1: Block diagram of ultrasonic measurement system.

2 ULTRASONIC MEASUREMENT SYSTEM

2.1 Algorithm of velocity measurement

UVP method can be divided into two methods. The one is UDM and the other is the UTDC. The UDM requires multiple ultrasonic emissions for obtaining the Doppler shift frequency [6]. The number of pulse (N_{pulse}) for the velocity calculation and the ultrasonic repetition frequency (f_{prf}) are usually set at 32-128 and 1-8 kHz. Hence, the time resolution is over 4 ms. On the other hand, the UTDC requires only two ultrasonic pulses for obtaining an instantaneous velocity distribution. If the f_{prf} is set at 1 kHz, the time resolution is 1 ms. Therefore, the UTDC is good for measuring the turbulent phenomena in a flow. However, the UTDC is easily affected by noises compared with the UDM. Hence, the UDM is suitable to make understanding or monitoring flow fields.

2.2 Measurement system of UDM and UTDC

In order to select the UVP algorithm, the system was developed as shown in Figure 1. The system composes of an ultrasonic pulser/receiver (JPR-2CH-KB, Japan Probe, Co., Ltd.), a high-speed digitizer (PXI-5114, National Instruments Corp.) and a PC. The measurement software was developed by using C++ and LabView. Ultrasonic is emitted by ultrasonic transducer (TDX) and the pulser/receiver. The reflected signals from seeded particles in water are digitized by the high-speed digitizer, and the signals are computed by the PC. The measurement software was made by the LabView, and instantaneous velocity distributions are confirmed at the software on time. The velocity algorithm of the UDM and the UTDC can be selected.

2.3 Experimental facilities

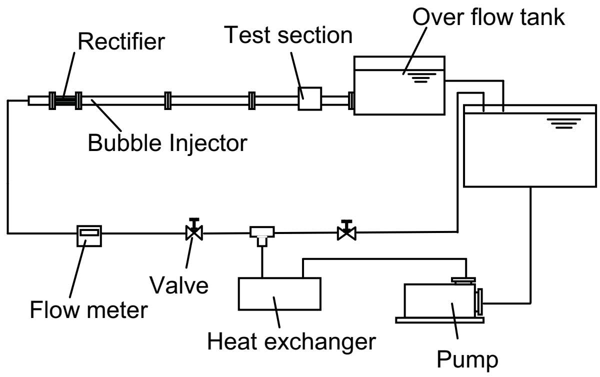
Experimental facility is shown in Figure 2. Experiments were conducted at a horizontal duct made of acrylic with 50mm –width and 25 mm –height. The working fluids were water and air (for two-phase flow), and the water temperature was kept at 20 – 25 °C. The water was seeded with nylon micro tracer particles at a ratio of 0.1 g/l. The specific density of these particles was 1.02 and the average diameter was 80 μm. The TDX was set at outside of the bottom of the test section. The TDX was submerged in the water in order to adjust the acoustic impedance. The basic frequency of the TDX is 8 MHz with sensor diameter of 3 mm.

3 VELOCITY MEASUREMENTS

3.1 Single-phase flow

In order to confirm accuracy of the developed system, velocity measurements in single-phase flow were conducted by using the UDM and the UTDC algorithm. Flow condition was Reynolds number (Re) of 8,000.

The results in the UDM are shown in Figure 3 and 4.



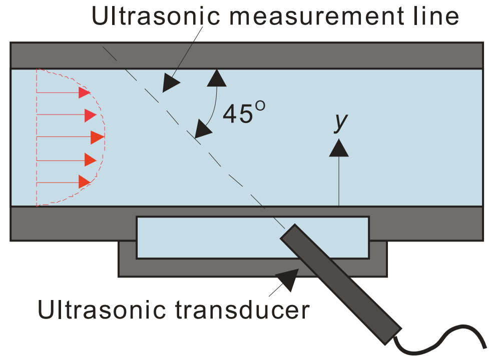


Figure 2: Test loop and the test section. The test loop is a horizontal duct with 50 mm –width and 25 mm –height. TDX was set at outside of the bottom with contact angle of 45°.

Number of instantaneous velocity profile was 10,000. The UDM parameters were N_{pulse} = 128 and f_{prf} = 8 kHz. Hence, 16 ms was required for obtaining the 128 reflected pulses. In the measurement, about 40 ms was taken for an instantaneous velocity profile including the calculation and the data storing time. Figure 3 shows the velocity histogram at center of the channel measured by the UDM. Total number of instantaneous velocity profile is 10,000. It can be confirmed that data of 0 m/s are counted. This means there were some data that could not measure the velocity at the position. In theoretically, the UDM algorithm cannot distinguish if there is not reflected signal or the velocity is 0 m/s at a position. For calculating the average velocity distribution, 0-data was eliminated from the all over the measured data as shown in Figure 4. For easy understanding, the horizontal axis indicates the average velocity, and the vertical axis indicates the distance from the bottom surface of the channel. It can be confirmed that the average velocity distribution could be obtained. However, it is difficult to distinguish between 0 m/s and no-data from the velocity histogram at lower velocity such as around near wall region. Therefore, the distinction method whether there is a particle or not is required for more accurate measurement.

A result measured by the UTDC is shown in Figure 5. In the experiment, f_{prf} was set at 1 kHz, and the time resolution was 1 ms. The black bar represents effective data number at the position. Although the total number of measurement is set at 20,000, obtained data changes with the position. If the reflected signal didn't obtained, or the calculated cross-correlation function is less than the setting values at a position, the velocity is recorded as no-velocity data. Therefore, the number of calculated velocity normally decreases with the distance from the TDX because the ultrasonic signal weakens. The method is difficult to obtain an instantaneous velocity distribution at all the measurement positions in the flow. In order to understand the flow field, ensemble average might be required. However, it can distinguish the data of 0 m/s and no-data. If the number of reflector particles is low, the average velocity distribution can be obtained. Therefore, the method is useful for measuring turbulent flow.

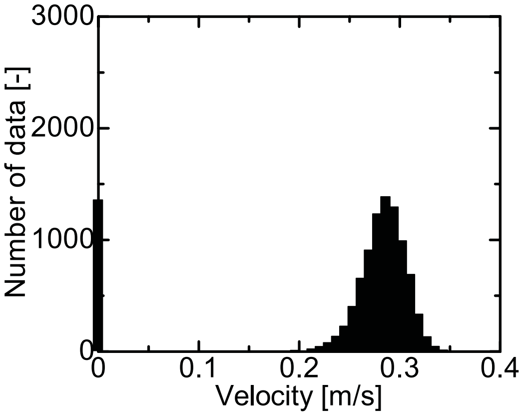


Figure 3: Velocity histogram at center of the channel. The data include 0 m/s which is no-data.

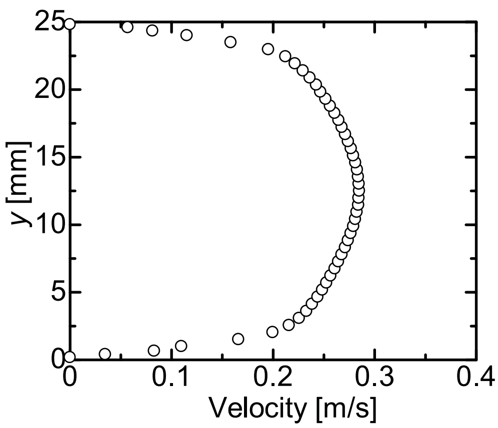


Figure 4: Average velocity distribution measured by using the UDM. 0-data was eliminated for averaging the velocity.

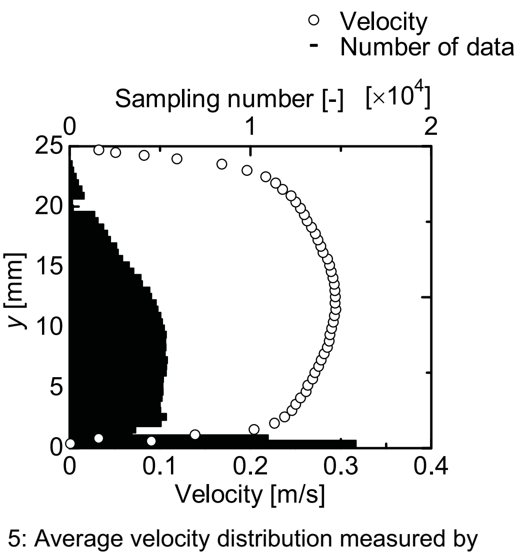
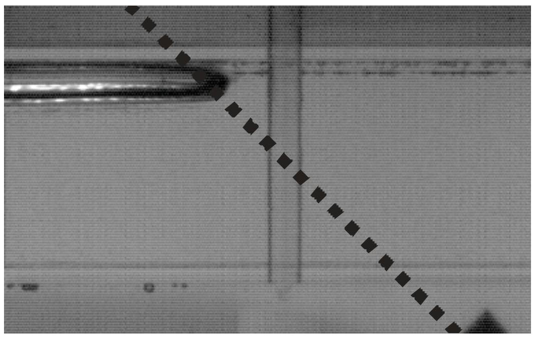


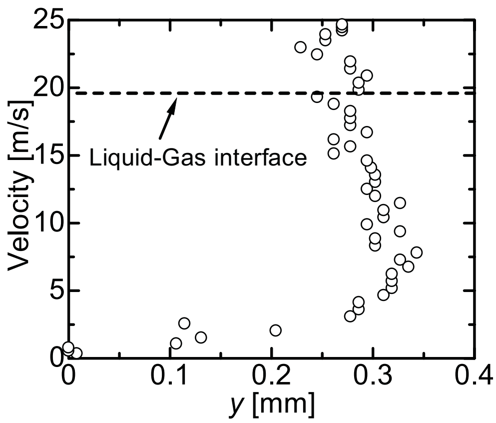
Figure 5: Average velocity distribution measured by using the UTDC. Number of data changes with measuring position.

3.2 Two-phase flow

In order to determine the liquid-gas interface, synchronized measurement of high-speed camera and the UDM was conducted. Frame rate of the high-speed camera was set at 500 fps, and the N_{pulse} and f_{prf} of the UDM were 128 and 8 kHz. For the UDM measurement, reflected signal was recorded continuously up to maximum onboard memory in the digitizer. After all the wave signals

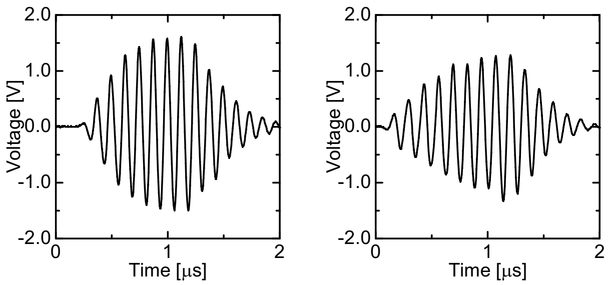


(a) A picture of two-phase flow taken by the high-speed camera.



(b) Instantaneous velocity distribution around the bubble nose.

Figure 6: Synchronized measurement of high-speed camera and the UDM in two-phase flow. The liquid-gas interface was determined by the picture.



(a) Water-Air interface (b) Water-Acrylic interface

Figure 7: Reflected signal from the interfaces

Table 1 Acoustic impedance of materials

	Acoustic impedance [kg/(m^2·s)]
Water	1.5×10^6
Air	4.3×10^2
Nylon-6,6	2.9×10^6
Acrylic	3.2×10^6

were recorded, instantaneous velocity distributions were calculated. As 32 waves were shifted from the previous calculation waves, velocity distributions were obtained every 2 ms.

A result of the measurement is shown in Figure 6. The superficial liquid velocity (J_L) was 0.24 m/s, and the superficial gas velocity (J_G) was 0.024 m/s. The flow regime was plug flow as shown in the picture. The bubble velocity obtained from the pictures was about 0.25 m/s. Synchronizing with the system, the liquid velocity distributions around a bubble could be obtained. It was observed that the bubble affects the liquid velocity, and the bubble induced the liquid turbulence. However, it is difficult to determine the liquid-gas interface from the instantaneous velocity distribution.

4 ANALYSIS OF ULTRASONIC REFLECTED WAVE

For applying the method for measuring two-phase flow in an opaque pipe, the synchronization with the high-speed camera cannot be applied. Therefore, identification method of liquid-gas interface by using the reflected signal was studied.

Figure 7 shows comparison of ultrasonic reflected signal from water-air and water-acrylic. It is confirmed that the phase of the wave changed in 180° depending on the interface. Because phase of the wave changes when the wave reflects on an interface from higher to lower acoustic impedance. Table 1 shows acoustic impedance of several materials. From the table, it is also confirmed that the reflected signal from nylon particles doesn't change the phase. If the phase detection technique is applied for the UTDC under low particle concentration, the reflection signal can be distinguished between liquid-particle and liquid-gas interfaces.

5 SUMMARY

In order to apply the UVP method for measuring two-phase flow, a system was developed. It can select velocity algorithms of the UDM and the UTDC. It was confirmed that the system can be used for measuring single-phase flow. In order to measure two-phase flow in a horizontal duct, the system was synchronized with a high-speed camera. The liquid velocity aroud bubbles were obtained by detecting the interface. In order to apply the technique for measuring two-phase flow in an opaque pipe, wave analysis of the reflected signals was studied. It was confirmed that the difference of the phase shift depending on the accousitc impedance might be used for identification of the interfaces.

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