Measurement of size and velocity of rising bubbles by a vector UVP

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We developed a vector UVP, composed of one emitter and two receivers, to measure the rising speed and the size of bubbles. A traditional UVP having one emitter and one receiver measures just a single velocity component and therefore it cannot exact the motion of rising bubbles moving three-dimensionally in the pipe. For example, to measure their rising velocity from a UVP installed on the outside wall of the pipe, we have to obtain at least two-dimensional velocity vector components of them. Our novel UVP can measure profiles with two-dimensional velocity vectors. As a demonstration, we installed the vector UVP to emit ultrasonic pulses horizontally and measured vertically rising bubbles in the still water. And the shape of bubbles was measured using the echo intensity obtained when calculating the Doppler frequency from echo signals from two receivers. Then, the size of bubbles was estimated from the rising velocity and the shape. From the comparison with optical visualizations, it is confirmed that the velocity was 15% underestimated and the size was corresponded with that of the visualizaiton, respectively.

Keywords: Bubble, Echography, Vector UVP

1. Introduction

Bubbles rising in a pipe flow can modify characteristics of the flow such as heat and momentum transfer coefficients, and therefore monitoring of bubbles' characteristics is required to control fluid machines. In most cases, invasive type measurement methods are not recommended since they give some damages to the pipe when their installation. Therefore, non-invasive type measurement methods are required for the monitoring [1]. Ultrasonic measurement techniques are one of them and several techniques have been developed to suit their targets of the measurement [2–5]. In many targets, especially, we focused on techniques to measure the rising velocity and the size of bubbles in the liquid. They are important parameters for estimating the void fraction and the drift velocity in two-phase flows. The simplest technique to obtain the rising velocity is the use of one transducer (TDX) of an ultrasonic velocity profiler (UVP) installed diagonally to the gravity direction [5]. Since it is assumed that rising bubbles have only one velocity component in this technique, if bubbles float vertically without any zigzag motion, we can measure their rising velocity correctly. However, if they move horizontally a bit, measured velocity includes a lot of errors causing the horizontal motion. In most cases, bubbles float with zigzag motions caused by their wake and the turbulence in a liquid-phase flow around of bubbles. To measure the rising velocity correctly, it is required to distinguish each velocity component by measuring them simultaneously. A vector UVP possible the simultaneous measurement is one of its solutions [7–9]. It is, however, not widely used for the measurement because many types of vector UVP generally use multiple receivers particularly designed for the UVP. TDXs using for the receiver have a small active area to keep highly the precision of angle θ been by ultrasonic waves reflected at the bubble. In this paper, we designed a vector UPV with typical type TDXs, used for a normal UVP and not designed for the vector UVP, by limiting measurable length from the TDX. Also it was estimated characteristics of rising bubbles by the new vector UVP.

2. Experimental method

2.1 Experimental setup

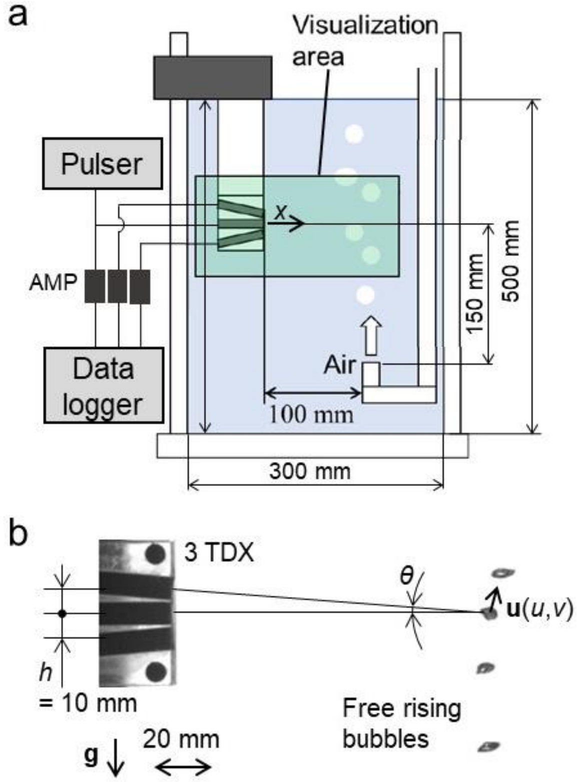

Figure 1: Experimental setup; (a) schematic diagram and (b) a snap picture of the visualization area.

The measurement of bubbles' characteristics by a vector UVP was performed in a water tank with an air tube installed at its bottom to inject bubbles as shown in Fig. 1. Three TDXs (TX4-5-8-40, Met-Flow) connected with three amps (PR-60BP, Japan-probe) and a data logger (PicoScope 3000, Pico Technology) were installed at 100 mm horizontally and 150 mm vertically away from the injector. Only the center TDX was set horizontally and connected with a pulser (JPR-600, Japan-probe) to use as the emitter. The others were set with ± 5° to the horizontal direction and vertically 10 mm away from the center TDX to make be toward a place where bubbles were passing on the measurement line; i.e, the place was 100–120 mm horizontally away from the center TDX in the experiment. The data logger recorded echo signals received from TDXs with a significantly high sampling frequency, 62.5 MHz, to resolve ultrasonic waves with 4 MHz in the basic frequency f_0. Detailed information on the setting parameter of each instrument is listed in Table 1.

Table 1: Parameters for the vector UVP.

Transducer (TX4-5-8-40, Met-Flow)		
basic frequency (f_0)	4	MHz
active diameter	5	mm
divergence half-angle	2.2	°
distance between TDXs	10	mm
angle of receiving TDX	± 5	°
Pulser (JPR-600, Japan-probe)		
cycle of ultrasonic pulse	4	
pulse repetition frequency	5	kHz
emission voltage	150	V
Data logger (PicoScope 3000, Pico Technology)		
sampling frequency	62.5	MHz
recording range of voltage	±0.2	V
resolution of voltage	12	bit

2.2 Conditions of bubbles

To verify the accuracy of rising velocity and size of bubbles obtained by the UVP, the optical visualization was performed simultaneously by a camera (FASTCAM Mini AX-50, Photron) as shown in Fig. 1(b). Results of the visualization are in Table 2, where the bubble size d_0 is the equivalent bubble diameter calculated from its projection area.

Table 2: bubble characteristics obtained by the optical visualization.

	average	standard deviation
Bubble size (d_o) [mm]	5.72	0.36
Rising speed (v_o) [m/s]	0.33	0.03

3. Signal processing

2.1 Detection of bubbles

Figure 2 shows echo signals obtained by a receiver. In the experiment, since there was no object possible to reflect ultrasonic pulses excepting bubbles, if there is a high amplitude in the echo signal, it indicates a bubble. At first, the intensity and the phase of echo pulses was estimated

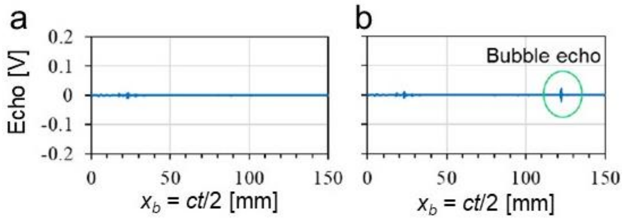

Figure 2: Received echo signals; (a) without bubbles and (b) with bubbles.

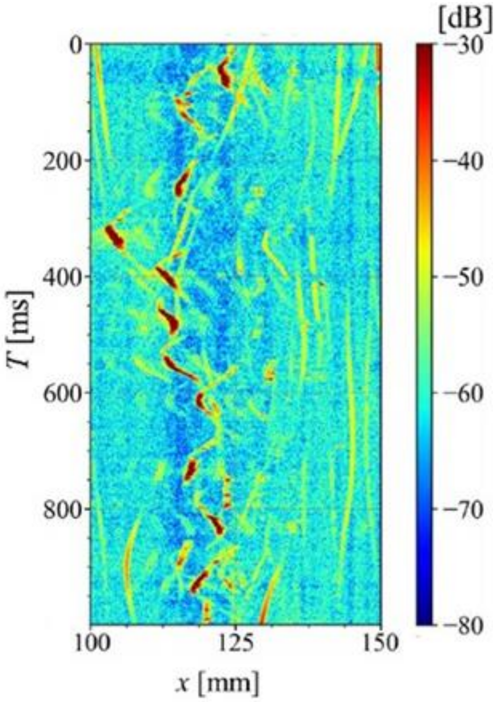

Figure 3: Averaged echo amplitude received by two receivers.

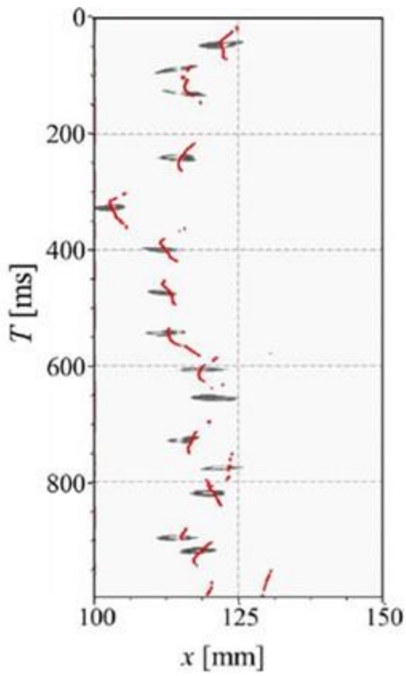

Figure 4: Time-line image at ultrasonic measurement line, where red plots show bubble surface detected by the averaged echo in Fig. 3.

the intensity and the phase of echo pulses was estimated from original echo signals by a demodulation with the Hilbert transform [10]. To detect bubbles from the signal, we decided a threshold value, 99 percentages outside intensity of echo without the bubble condition, and judged as the bubble interface when averaged echo intensities obtained from two receivers is over the threshold. Figures 3 and 4 show time-line images of averaged echo intensity calculated by the demodulation and bubbles visualized optically by the camera. In Fig. 4, positions of the intensity higher than the threshold intensity are expressed as red plots and therefore they mean the left side interface of bubbles. Comparing bubbles and red plots in the figure, it is confirmed that this detection method is working well although acoustically detected bubbles are larger than optically visualized bubbles. The long existence time of bubbles estimated by the vector UVP is caused by a high echo intensity on the gas–liquid interface of bubbles. This high intensity occurs even if they block a part of the ultrasonic beam with a thick diameter, over 5 mm in the experiment, as shown in Fig. 5 and therefore bubbles are detected by the UVP before they reach the center axis of the beam.

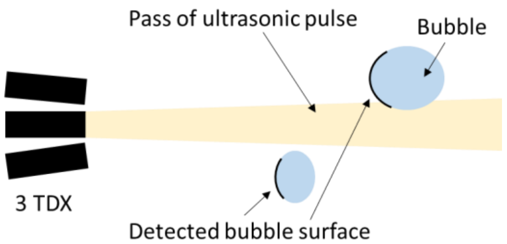

Figure 5: Ultrasonic pulse reflection at bubble surface toward to TDX, where the pulse reached at the surface on upper and bottom side of bubbles cannot return to receiver because of its shallow reflect angle.

2.2 Estimation of rising velocity

To obtain rising velocities of the bubble, at first, the Doppler shift frequency f_D should be estimated from the echo signal. Already many estimation methods were suggested and, here, the Doppler spectra analysis using DFT was employed for the estimation [11]. And then, the rising velocity v was calculated by Eq. (1).

$$v = \frac{c\left(f_{D1} + f_{D2}\right)}{2 f_0 \sin\theta} = \frac{h\left(f_{D1} + f_{D2}\right)}{f_0 t_b} \tag{1}$$

Here, c, h and θ are the speed of sound, the distance between transducers and the angle in the pass of ultrasound as shown in Fig. 1. The result of v is shown in Fig. 6. upper-ward and down-ward velocities exist in the acoustically detected bubble surface, but there are almost zero velocities in the other areas. It is supposed that down-ward velocities in the surface is actually upper-ward velocities faster than the maximum velocity which UVP is possible to measure. In the UVP measurement, plus and minus signs is changed the velocity is higher than the maximum measurable velocity of UVP. The rising velocity of individual bubbles was defined as the average of upper-ward velocities on surface of each bubble.

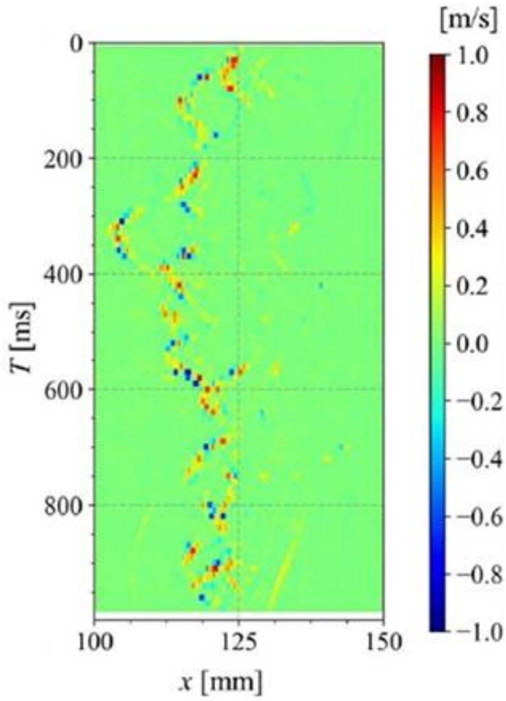

Figure 6: upper-ward velocity component from the vector UVP.

2.3 Estimation of bubble size

We already know the existence time of each bubble passing on the ultrasonic beam and its rising velocity and therefore the simplest method to estimate bubble size is the multiplication of them. But it includes some errors caused by the beam thickness and non-detected surface on upper and bottom area of bubbles as shown in Fig. 5. An error caused by the beam thickness is possible to reduce its effects on the bubble size estimation because the thickness and the rising velocity are knowing values. However, it is hard to reduce the effects caused by the non-detected surface because we do not have information of bubble shape. Therefore, we tried to estimate the bubble size from shape of a part of the interface on its side area by assuming that all bubbles had elliptical shapes. The elliptical shape was fitted on the part of detected interface. In the fitting, unknown parameters were the temporal-spatio center positions, major and minor diameters of the ellipse, and its tilted angle. Because of five unknown parameters, the fitting was performed only when more than four plots of the detected surface existed continuously in the time. Bubbles composed with less than five plots were treated as the error and deleted in the measurement result. The size of each bubble was calculated as the equivalent diameter from the major and minor diameter of its fitted ellipse.

5. Evaluation of the measurement

Averages of the bubble size and the rising velocity measurend are in Table 2. Comparing with results of the optical visualizaiton in Table 1, the bubble size has the same value and the rising velocity is 0.05 m/s, 15.1%, lower in the vector UVP measurement, respectivley. Although the size estimation by the UVP is well matched with that of the visualization, the standard deviation of size becomes 4.6 times larger. To understand why the gap occurs, probability density funtions (PDF) of the bubble size are shown in Fig. 7. Although the bubble size is actually in 5–6.5 mm, the size estimation by vector UVP shows it is in 3–9.5 mm. It is supposed that the large standard deviation is caused by the shape of bubbles. In the estimation, we assumed that the shape of bubbles was elliptical. As shown in Fig. 1(b), however, bubbles did not have elliptical shapes, because their size was significantly large and bubbles did not maintain elliptical shapes by the surface tension.

Table 2: bubble characteristics obtained by the vector UVP.

	average	standard deviation
Bubble size (d_u) [mm]	5.72	1.67
Rising speed (v_u) [m/s]	0.28	0.40

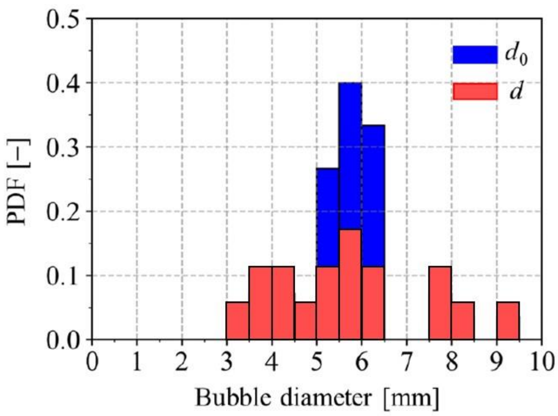

Figure 7: Probability density funtions of the bubble size.

5. Summary

We tried to estimate the size and rising velocity of floating bubbles in water by a vector UVP composed with three typical transducers using a normal UVP ; one transder was working only as emitter and the others were wokinig as recivers. This vector UVP allows use of typical transducers as a reciver by giving a limitaion of measuremnt area and an angle to transducers to face the measurement area. The bubble surface was detected using strong echo from the surface. And the rising velocity of a bubble was defined as an average value of vertical velocities located in the detected bubble surface. This rising velocity was about 15% underestimated compring with the actual rising velocity. The bubble size was estimated using a fitting of ellipse defined from a shape of the detected surface and the rising velocity. An average of bubble size obtined from the UVP was well matched with that of their actual sizes although the standard deviation of sizes were 4.6 times overestimated by this measutement because the shape of bubbles were not keeping elliptical shapes in the experiment. It is supposed that our size estimation method provies better results in a case with small bubbles keeping elliptical shapes. In a case with large bubbles like as this experiment, however, it is required to develop a different method to estimate the bubble size.

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