13th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering
Zürich, Switzerland (13.-15. June 2021)

# Vertical bubbly pipe flow measurement using combined signal of ultrasonic Doppler and echo intensity profiles

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A method for measuring the void fraction in bubbly two-phase flow rising in a vertical pipe is proposed. The method utilizes both velocity and echo intensity profiles in combination so that liquid phase velocities and gas–liquid interfaces are obtained simultaneously. The velocity profile is processed with Sobel filter to detect peculiar local flow around individual bubbles and it helps to detect bubbles. The echo intensity profile is normalized by background echo of single-phase flow condition to exclude weak signals. This also realizes bubble detection with an appropriate threshold. These two kinds of information for bubble detection are combined into a single scaler field on space-time domain, to which a new threshold is given to accurately find the bubbles dispersed in the pipe. We demonstrate this technique using a vertical bubbly two-phase pipe flow with a diameter of 50 mm using a single ultrasonic transducer at 4 MHz in the basic frequency. A parametric study is conducted changing gas flow rate up to 1% in bulk void fraction. As a result, the error to be about 0.1%.

**Keywords:** UVP, void fraction, bubbly flow, bubble detection, echo, Doppler

## 1. Introduction

Airlift pumps utilizing upward force given by air bubbles to transport liquids are currently investigated as a technology for pumping mud containing rare-earth element (REE) from the deep sea. Its transportation cost and efficiency are affected by many factors such as length and diameter of the pipe, amount of the injected air, and the injection location. It is therefore necessary to set these parameters appropriately for keeping sufficient performance. For seeking the appropriate parameters, a real-time measurement of the flow rate of each phase in the pumping pipe is required. Since the pipe is made of metal and the fluid inside is expected to be opaque, the applicable measurement method is limited. In this study, we focused on ultrasonic Doppler velocity profiling (UVP), which can obtain the velocity distribution in the pipe in real-time non-invasively.

Since the airlift pump is applied to a vertical pipe and the particle size of REE mud to be pumped is small[1], we simplify the flow in the pipe as a gas-liquid two-phase flow in a vertical pipe. Since various methods have been proposed for determining the flow pattern of multiphase flows, we adopted a procedure in which the flow regime is determined by some methods[2]-[4], and then the measurement appropriate for each flow regime is performed. In this paper, we propose a measurement method focusing on bubbly flow. One of the main parameters characterizing this flow is the void fraction. In this paper, we propose a method to estimate the void fraction by detecting the bubble position using the instantaneous velocity and echo intensity distributions obtained by UVP. Bubble distributions are then calculated using a statistical method.

## 2. Methods

Ideally, ultrasonic wave is specularly reflected at the gas-liquid interface for bubble diameters larger than the wavelength of the ultrasonic wave[5]. It is therefore difficult to measure bubbles behind a bubble existing on the measurement line. Murai et al. proposed a statistical method to estimate the bubble distribution in measurement line from detected bubbles located at the closest position on the line from the ultrasonic transducer (TDX)[6]. In this paper, we adopt this method to estimate the void fraction in the vertical bubbly pipe flow.

### 2.1 Bubble detection

There are two possible ways to detect bubbles using UVP; one is to use the velocity distribution of the liquid phase, and the other is to use the echo intensity distribution. The two methods are processed in the following way and used for bubble detection. To detect bubbles from the velocity distribution, the Sobel filters with three velocity elements in velocity profiles on each of temporal and spatial directions were used to emphasize the sharp velocity gradient existing near the bubble. For the bubble detection using the echo intensity distribution, since it is known that ultrasound pulses are strongly reflected by bubbles[7][8], the normalized echo intensity distribution $I_n(r;t)$ is obtained using Eq. (1) to better emphasize the strong signal. Here, $I_{ave}$ is the time-averaged echo intensity distribution and $\sigma$ is the standard deviation of a single-phase flow with the same liquid-phase velocity. $I(r;t)$ is measured echo intensity distribution at each time $t$.

$$\begin{cases} I_n(r;t) = \left|\dfrac{I(r;t) - I_{ave}}{\sigma}\right| - 1, & \text{if } \left|\dfrac{I(r;t) - I_{ave}}{\sigma}\right| > 1 \\ I_n(r;t) = 0, & \text{otherwise} \end{cases} \quad (1)$$

After these processes, the sharp velocity gradient and strong echo intensity around the bubble are detected by setting appropriate threshold values, and thus the bubble position is estimated.

In addition to the above methods, we attempted to

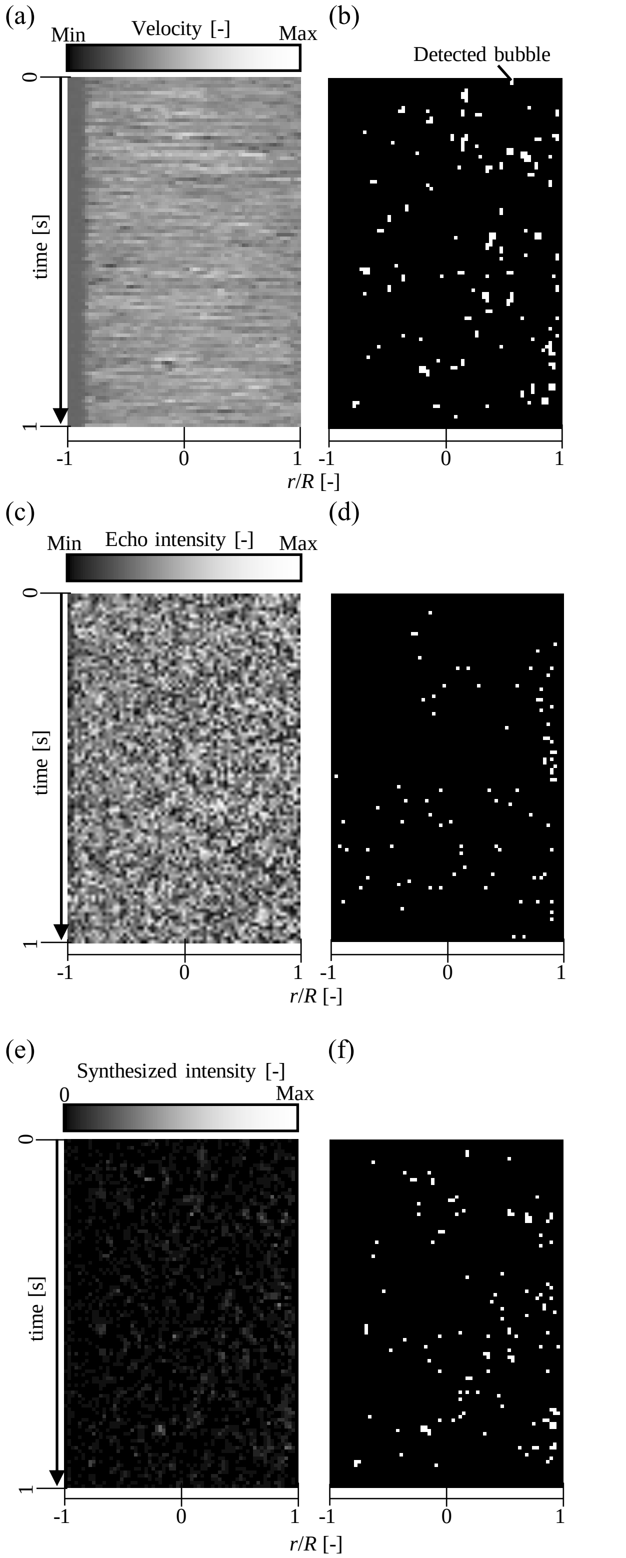


Fig 1: (a) Velocity distribution of the liquid phase, (b) detected bubbles from (a) using the Sobel filter as white points, (c) the echo intensity distribution, (d) detected bubbles from (c) using a threshold as white points, (e) the synthesized distribution $D_{\mathrm{blend}}$ ($w = 0.50$), and (f) detected bubbles from (e) using a threshold as white points. $r$ means distance from the center of pipe and $R$ means the radius of pipe. All images are under the condition of $j_L = 1.2\,[\mathrm{m/s}]$.

improve the accuracy of the detection of positions by synthesizing the filtered velocity distribution $V_{Sobel}$ and normalized echo distribution $I_n$. It is expected that it supplies an improved accuracy comparing with that using only one distribution even if the distribution includes some noises because of the complementary use of two distributions. The synthesized distribution $D_{\mathrm{blend}}$ is expressed by Eq. (2).

$$D_{\mathrm{blend}} = (1 - w)V_{Sobel} + wI_n \tag{2}$$

In the equation, the weight coefficient $w$ was varied in 0.01 increments over the range in $0 \leq w \leq 1$. Figure 1 shows the images of the velocity, echo intensity, and synthesized distributions before and after the processing.

### 2.2 Evaluation

To evaluate the positional accuracy of the bubble detection, each bubble distribution is compared with simultaneously visualized images. Figure 2 shows two timeline images; one is made by the optical visualization and indicates bubbles as dark areas, and the other is made from $D_{\mathrm{blend}}$ and shows the location of the gas–liquid interface closest to the TDX estimated from the UVP data as red points. Since TDX is located on the left side of the figure, ideally, the location of the closest gas–liquid interface is at the left edge of the black areas. Therefore, if the difference between the positions of the red dot and the left edge of black areas is small at each time, it means that the accuracy is high. In order to estimate the accuracy quantitatively, we define an error as shown in Eq. (3).

$$error = \frac{1}{T}\int_0^T \frac{|d_{\mathrm{timeline}}(t) - d_{\mathrm{UVP}}(t)|}{2R}\,\mathrm{d}t \tag{3}$$

In the equation, $d_{UVP}$ is the position of the red dot, $d_{timeline}$ is the leftmost position in the black area, and $T$ is the measurement time. Note that the position in the case of no bubble detected is set as $2R$.

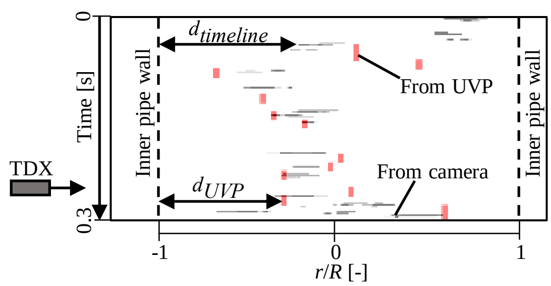


Fig 2: Bubble positions by UVP (red points) and optical visualization (black areas) for $j_L = 1.2\,[\mathrm{m/s}]$.

### 2.3 Bubble reconstruction

Based on the distribution of bubbles closest to TDX obtained in the previous section, the bubble distribution inside the pipe was estimated by the statistical method suggested by Murai et al.[6]. There are many measurement points of UVP inside the pipe according to its spatial resolution and, here, we designated these points as from 1 to $N$ in order of proximity to TDX. From the bubble distribution obtained from the UVP, the probability $\beta_n$ at measurement point $n$ that the bubble closest to TDX exists at each measurement point is calculated. The actual probability $\alpha_n$ at $n$ can be expressed as a function of $\beta_n$, Eq. (4), regardless of whether it is closest to TDX or not.

$$\beta_n = \alpha_n \prod_{k=1}^{n-1} (1 - \alpha_k) \tag{4}$$

This equation can be rewritten as Eq. (5) by the equation transforming.

$$\alpha_n = \frac{\beta_n}{1 - \sum_{k=1}^{n-1} \beta_k} \tag{5}$$

It gives the distribution of bubbles in the pipe along the measurement line. Assuming that this distribution is symmetrical about the central axis of the pipe, the void fraction can be calculated by integrating it over the pipe cross-section.

## 3. Model experiments

To confirm efficacy of the present method, model experiments were performed. Then, error and void fraction were calculated by the method.

### 3.1 Experimental setup

Figure 3 shows the overall view of the experimental facility and the enlarged view of the water jacket. An acrylic pipe with $2R$ = 50 mm in the inner diameter, 5 mm in the wall thickness, and 2000 mm in the length was used for the experiment. The TDX was installed in the water jacket to avoid the effect of ultrasonic refraction at the acrylic wall on the UVP measurement. Also it was set at 70 mm from the pipe wall to avoid the low ultrasonic intensity area near the TDX, and the angle of inclination was set at 5° to allow for the velocity measurement range. The ultrasonic basic frequency was 4 MHz. Velocity and echo intensity distributions were measured by an ultrasonic velocity profiler (UVP-DUO, Met-Flow). For comparison with the ultrasonic measurement, a high-speed video camera (FASTCAM Mini AX50, PHOTRON) and a sheet red laser (DPRLu-5W, Japan Laser Co., Ltd.) were used to visualize the flow on the measurement line of UVP. During the experiment, water containing tracer particles (HP20SS, Mitsubishi Chemical Corporation) was raised in an acrylic pipe and the air was injected from near the bottom of the pipe. The apparent flow velocity $j_L$ in the liquid phase was set as two conditions (1.2 and 2.0 m/s), and the apparent flow velocity $j_G$ in the gas phase was fixed at 0.010 m/s. Void fractions estimated from $j_L$ and $j_G$ were 0.83% and 0.50% respectively. Single-phase flow was also measured at each liquid-phase velocity condition to be used for normalization of the echo intensity described in Section 2.1.

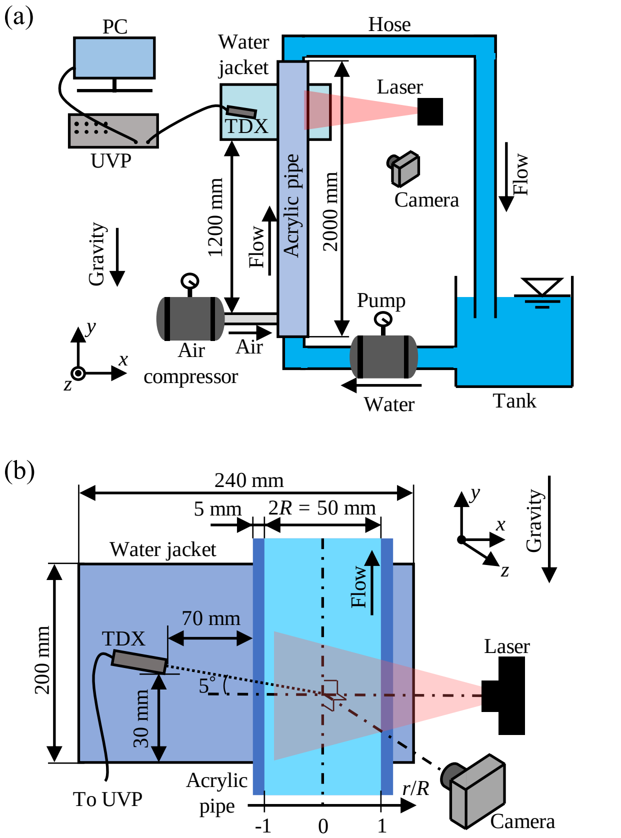


Fig 3: (a) Schematic overview of experimental setup, and (b) enlarged image around the water jacket.

### 3.2 Results

First, the accuracy of bubble detection using the two distributions is compared with that using the synthesized distribution in terms of the value of error. Figure 4 shows the error values of the velocity distribution alone, the echo intensity distribution alone, and the synthesized distribution under two liquid velocity conditions, $j_L$ = 1.2 and 2.0 m/s. $w$ in the synthesis is set so that error takes the minimum value: $w$ = 0.50 at $j_L$ = 1.2 m/s, and $w$ = 0.25 at $j_L$ = 2.0 m/s. If the value of error is smaller when the distributions are synthesized, it can be said that the bubble detection accuracy is improved by the synthesis. When void fraction was high, the value of error was reduced by the synthesis. In the other case, however, there was no noticeable difference between the synthesis and the velocity distribution alone. This means that when the void fraction is very low, bubbles can be identified accurately by the velocity profile alone, but when the void fraction is relatively high, the accuracy decreases relatively. In addition, the accuracy of synthesis increases to use the echo intensity auxiliary. The reason for this is as follows. As the void fraction increases, the distance between bubbles narrows and the flow around the bubbles interferes with each other, and therefore the accuracy of bubble detection by the velocity distribution becomes lower. On the other hand, since the internal processing process of the echo intensity output by the UVP-duo used in this paper is unknown, the accuracy of bubble detection based on echo intensity alone is low. However, as can be seen from the figure, the change in accuracy with the change in void fraction is small. Therefore, as the void fraction increases, the detection accuracy by the synthesis is considered to increase relatively. The bubble distribution with the smallest error in each condition was used to restore the bubble distribution. Assuming that the restored bubble distribution was axial in the pipe, the void fraction was estimated. The estimated void fraction is shown in Fig. 5. The error in the estimated void fraction was about −0.1% for both velocity conditions. The small value of the estimated void fraction indicates that there were many undetected bubbles and that the bubble detection position by the UVP was farther from the center of the pipe than the actual bubble position.

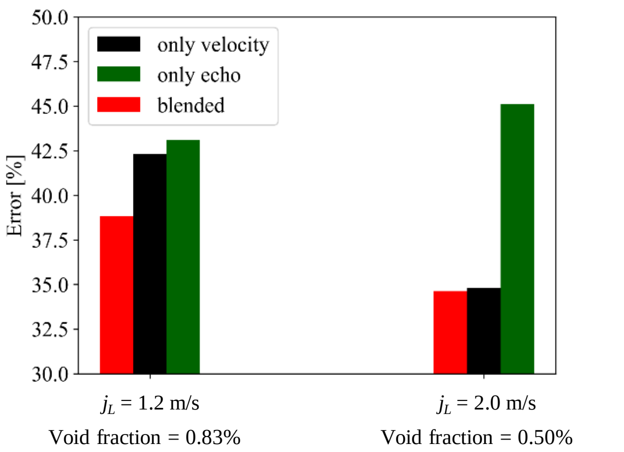


Fig 4: Change in error due to different methods of acquiring bubble distribution under two conditions. (High void fraction: $j_L$ =1.2 m/s, void fraction is 0.83 %, Low void fraction: $j_L$ =2.0 m/s, void fraction is 0.50 %) Red bar shows the error values of blended distribution, black shows that of the velocity distribution alone, green shows that of the echo intensity distribution alone.

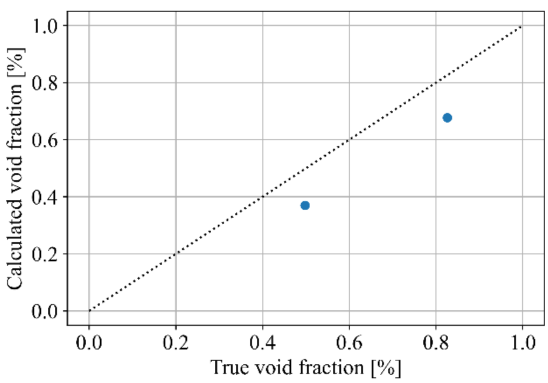


Fig 5: Calculated void fraction of both condition as blue dots. Closing to dotted line, decreasing calculation error.

## 4. Summary

In this paper, we developed a method to estimate the void fraction of bubbly flows in a vertical pipe by acquiring the bubble distribution using velocity and echo profiles obtained from UVP and a weighted coefficient. Its accuracy of detected bubble position was evaluated by comparing with simultaneous images taken by the optical visualization. As a result, accuracy of the present method was improved about 5% in a bubbly flow with a high void fraction, 0.83%. In the condition with a low void fraction, 0.50%, the accuracy was almost similar to that using only velocity profiles without echo information. In all measurements, the accuracy of void fraction estimated using the acquired bubble distributions was within 0.1%. The present method has some problems to solve as future works; one is a high error rate of bubble location detected by the ultrasonic measurement and the other one is how to judge the weighted coefficient. The former can be solved by measuring with higher time resolution, and the latter can be solved by finding some law for the value of *w*.


## Acknowledgment

This research is financially supported by New Energy Develop Organization (NEDO), Japan (C.N. 19101191-0). The authors thank to Mr. T.Sampo and Mr. D. Yoon for their technical supprots.


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