Ultrasonic Measurement of Velocity Profile on Bubbly Flow Using Fast Fourier Transform (FFT) Technique

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Abstract. In two-phase bubbly flow, measurement of liquid and bubble velocity is a necessity to understand fluid characteristic. The conventional ultrasonic velocity profiler (UVP), which has been known as a nonintrusive measurement technique, can measure velocity profile of liquid and bubble simultaneously by applying a separation technique for both phases (liquid and bubble) and transparent test section is unnecessary. The aim of this study was to develop a new technique for separating liquid and bubble velocity data in UVP method to measure liquid and bubble velocity profiles separately. The technique employs only single resonant frequency transducer and a simple UVP system. An extra equipment is not required. Fast Fourier Transform (FFT) based frequency estimator paralleled with other signal processing techniques, which is called as proposed technique, was proposed to measure liquid and bubble velocity separately. The experimental facility of two-phase bubbly flow in the vertical pipe was constructed. Firstly, the Doppler frequency estimation by using the FFT technique was evaluated in single-phase liquid flow. Results showed that FFT technique showed a good agreement with autocorrelation and maximum likelihood estimator. Then, separation of liquid and bubble velocity was demonstrated experimentally in the two-phase bubbly flow. The proposed technique confirmed that liquid and bubble velocity could be measured efficiently.

1. Introduction

Bubbly flow has been more attractive to many researchers to investigate its property. Some parameters of the phenomena have complicated to understand such as a liquid flow rate and the bubble motion. To understand the characteristic of two-phase bubbly flow, the important parameters in two-phase bubbly flow i.e. velocity are necessary to be known accurately. The velocity profile of liquid and bubble in bubbly flow is an important parameter to signify fluid characteristic, relate with liquid flow rate, and bubble motion. Hence, classification of liquid and bubble velocity is a necessity. Several intrusive techniques were utilized in two-phase flow such as hot-film anemometry [1]. This technique disturbs the flow, and intrusive effects on flow structures reduce its lifetime. To eliminate these effects, many nonintrusive measurement techniques have been developed, such as laser Doppler anemometry (LDA) [2] and Particle Image Velocimetry (PIV) [3]. Nonintrusive measurement methods have usually used for the measurements of the rising velocity of a single or few bubbles. Moreover, these measurement techniques for velocity measurements require transparent test section, and it obviously fails if working fluid is opaque.
The ultrasonic measurement technique is a powerful tool to obtain the flow characteristic. It is a nonintrusive method and capable of measuring velocity profile on the non-transparent test section. Ultrasonic Velocity Profile (UVP) measurement uses a pulsed echography of an ultrasonic wave reflected from reflector such as small particle dispersed in a liquid to measure an instantaneous velocity profile along its measurement line. Takeda et al. [4] originally developed the UVP method to measure single-phase liquid flow. The advantage of this technique is that it can perform spatial-temporal measurements of the flow. Aritomi et al. [5] developed a system, which combined the UVP system and video data processing unit to measure the liquid velocity distributions in bubbly flows, the average bubble diameter, and the void fraction. They proposed the detection of bubble positions if bubbles cross the ultrasonic measuring line by applying statistical methods to the UVP. When the UVP method was applied to measure two-phase bubbly flows, the echo signal reflected by both the dispersed small particles in the liquid phase and the bubble. Hence, the velocity data measured by the UVP method included velocity information of both phases. Suzuki et al. [6] developed a phase-separation technique using the UVP method. The method applied to pattern recognition to distinguish a phase of the velocity profile. Yamanaka et al. [7] tried to develop a separation technique, which based on the differences of ultrasonic intensity of signals reflected from tracer particles and bubble. Ultrasonic intensity reflected from a bubble’s surface is stronger than a small particle dispersed in a liquid. It is due to the differences in acoustic impedances and diameters between them. Later on, Murakawa et al. [8] employed multi-wave TDX transducer and time domain cross-correlation method (UTDC) to separate liquid and bubble velocity profile. This technique could synchronise the instantaneous velocities of liquid and bubbles. Some measurement technique for two-phase bubbly flow by UVP was developed to measure velocity profile of bubbly flow, and their system requires several types of equipment. For instance, the measurement system combines the UVP system and video data processing unit [5], and two basic frequencies were required [8]. As a consequence, the number of pulser-receiver and accessories has been doubled or more. Therefore, the measurement system will be complex, and furthermore, the cost will also be higher.

In this paper, we study the effect of bubbly flow that influences to the Doppler signal in Doppler pulse repetition method. The size of the bubble and small particle in bubbly flow are significantly different (bubble is bigger than small particle $10^3$ times), and its effects on Doppler signal amplitude size. Also, Doppler shift frequency, which obtains from the bubble and small particle, are different due to their velocities difference. As a result, multi-frequency and different amplitude of Doppler signal are observed. Therefore, our purpose is to develop a powerful signal processing techniques such as Fast Fourier Transform (FFT), Windowing and Signal Enveloping, to separate instantaneous velocity profile of both bubble and liquid. The proposed technique analyses multi-frequency and different amplitude phenomena of Doppler signal using single transducer. Also, it provides not only velocity data but also bubble diameter and number of bubble data. In this study, the classification of liquid and bubble velocity is demonstrated experimentally.

2. Methodology

2.1. Ultrasonic Velocity Profile (UVP) principle

The UVP method can obtain instantaneous velocity profiles of fluid, and flow rate can be calculated by integrating the measured velocity profile over a pipe or channel diameter. An ultrasound pulse is emitted from transducer along the measurement line, and the echo reflected from the surface of the reflector such as small particle is derived in the same transducer. The position of a particle can be calculated from the speed of sound $c$ and traveling time of ultrasound $\tau$ from the start of the pulse burst to its reception.

$$x = \frac{c\tau}{2}$$

The particles in working fluid follow the main flow, and its density is nearly equal to water (0.98 g/cm$^3$). Therefore, the velocity of a particle is assumed to be same as the velocity of fluid at that position. The
echo signal received from moving particles contains Doppler shift frequency \( f_D(x) \) and the velocity of particle \( V(x) \) is described as

\[
V(x) = \frac{c f_D(x)}{2 f_0 \sin \theta}
\]

(2)

where \( f_0 \) is the basic frequency of ultrasound and \( \theta \) is the incident angle.

2.2. Doppler pulse repetition method and Doppler signal

Over a decade, Doppler pulse repetition method has been used to extract Doppler signal from echo signal reflected by the reflector under a certain number of repetitions (\( N_{\text{rep}} \)). This Doppler signal is used to estimate Doppler frequency respectively. Figure 1 shows a block diagram of UVP system based on Doppler pulse repetition technique. An ultrasonic pulser/receiver, operated in a pulse-echo mode, emits ultrasonic pulses through an ultrasonic transducer. Then, the echo signal received by the transducer are sent to pulser/receiver. In quadrature demodulation, the echo signals from the output of pulser-receiver are multiplied by the cosine and sine function separately to detect flow direction (forward and backward), a low-pass filter (LPF) is applied to eliminate the carrier wave components of basic frequency, and extract the Doppler signal. Frequency estimation section computes Doppler frequency, and finally, velocity can be calculated by equation (2).

![Figure 1. Block diagram of UVP system based on Doppler pulse repetition technique.](image1)

Doppler signal is obtained from echo signals reflected by the reflector in liquid; the reflector can be particle or bubble. Its frequency and amplitude inform the velocity and position of moving reflector respectively. In the case of bubbly flow, the size of the bubble and small particle are different, and its effects on the size of Doppler amplitude. Also, Doppler shift frequency which is obtained from the bubble and small particle are different due to their velocities difference. The bubble has a lower density than water and density of the particle is nearly equal to water (0.98 g/cm\(^3\)). Thus, bubbles move faster than particles. In some cases, the position of bubble and particle occurs in same measurement channels concurrently along the number of repetition (\( N_{\text{rep}} \)). In this case, it is difficult to distinguish their

![Figure 2. Multi-frequency and different amplitude effect of Doppler signal.](image2)
velocities. When this phenomenon occurs, multi-frequency and different amplitude of Doppler signal will be generated as shown in figure 2. Therefore, to separate velocity profile of both bubble and particle, powerful signal processing in post processing is required to analyze the effect of Doppler signal.

2.3. Doppler frequency estimation using Fast Fourier Transform (FFT)

The Fast Fourier Transform (FFT) was widely used in the conventional frequency measurement. It is selected as Doppler frequency estimator in this study and called as “FFT-based frequency estimator.” The power spectrum of the frequency \( P(f_k) \) is demonstrated as follows:

\[
P_f = \left[ \text{Re}[X_L] - \text{Im}[X_Q] \right]^2 + \left[ \text{Re}[X_Q] + \text{Im}[X_L] \right]^2
\]

(3)

\[
P_b = \left[ \text{Re}[X_L] + \text{Im}[X_Q] \right]^2 + \left[ \text{Re}[X_Q] - \text{Im}[X_L] \right]^2
\]

(4)

where \( \text{Re} \) and \( \text{Im} \) are a real and imaginary number, \( X_L(f_k) \) and \( X_Q(f_k) \) are the discrete Fourier transforms of the frequency demodulation, \( P_f \) and \( P_b \) are power spectra of a forward direction and backward direction respectively. The value of Doppler frequency \( f_D \) can be computed by averaging the spectrum as follows:

\[
f_D = \frac{\sum_{k=0}^{N_{rep}} f_k \left( P_f(f_k) - P_b(f_k) \right)}{\sum_{k=0}^{N_{rep}} \left( P_f(f_k) + P_b(f_k) \right)}
\]

(5)

where \( N_{rep} \) is the number of repetitions of signal emission.

2.4. Separation of particle and bubble velocity

Particle and bubble velocities are known separately by using proposed technique, which is called “Proposed FFT” as illustrated in figure 3. The technique based on the integration of FFT-based frequency estimator and several signal processing such as Windowing, Enveloping, and Threshold defining. The proposed technique is not only used to estimate the frequency of Doppler signal, which is extracted from quadrature demodulation section. Furthermore, the proposed technique is performed for analyzing both frequency and amplitude of the signal. As phenomena of Doppler signal in bubbly flow was explained in section 2.2, a separation of particle and bubble velocity is possible by replacing frequency estimation section in figure 1. Doppler signals on both forward and backward direction received from the quadrature demodulation section are divided into several windows \( W_n \). Doppler signals in each window are sent to FFT-based frequency estimator to calculate the Doppler frequencies and are sorted to be array form \( (f_{ki}) \) as follows:

\[
f_{Di} = \frac{\sum_{k=\frac{N_{rep}}{W_n}W_n}^{\frac{N_{rep}}{W_n}W_n-1} f_k \left( P_f(f_k) - P_b(f_k) \right)}{\sum_{k=\frac{N_{rep}}{W_n}W_n}^{\frac{N_{rep}}{W_n}W_n-1} \left( P_f(f_k) + P_b(f_k) \right)}
\]

(6)

\[f_D = [f_{D1}, f_{D2}, ..., f_{Dn}]\]

(7)

where \( i = 1, 2, 3, ..., n \) is window index, and \( W_n \) is the number of windows.

On the other hand, the amplitude of Doppler signal in each window is known by making the envelope of the Doppler signal \( (e_i(i)) \) in the forward direction using Hilbert transform. The maximum of signal amplitudes in each window are arranged in array form \( (a_i) \) as equation (8) and (9); index number \( (i) \)
\( e_i(t) = (\hat{s}_i^2(t) + \hat{s}_i^2(t))^{1/2}; \quad \hat{s}_i(t) = H[s_i(t)] \) is the Hilbert Transform

\[ a_i = \max(e_i(t)) \] (9)

\[ f_{Dh} = \begin{cases} f_{Db} & \text{if } a_i \geq \text{Threshold} \\ f_{Dp} & \text{if } a_i < \text{Threshold} \end{cases} \] (10)

\[ f_{D(bubble)} = [f_{Db}, f_{Db-1}, \ldots, f_{Db-(l-1)}] \] (11)

\[ f_{D(part)} = [f_{Dp}, f_{Dp-1}, \ldots, f_{Dp-(m-1)}] \] (12)

\[ \bar{f}_{D(bubble)} = \frac{f_{Db} + f_{Db-1} + \ldots + f_{Db-(l-1)}}{l} \] (13)

\[ \bar{f}_{D(part)} = \frac{f_{Dp} + f_{Dp-1} + \ldots + f_{Dp-(m-1)}}{m} \] (14)

where \( l \) is the number of bubble Doppler frequency and \( m \) is the number of particle Doppler frequency.

**Figure 3.** Block diagram of proposed algorithm to separate liquid and bubble velocity.
identifies window number. The data from each index is compared with the threshold value as equation (10); threshold value is defined to be higher than the maximum of Doppler amplitude of small particle, in which analyses of statistical data of 100,000 Doppler signals were only generated from small particles. Then, the index number of amplitude data will be separated into two categories. Firstly, if the amplitude value is higher than the threshold, its index will be defined as an array index of the bubble. Secondly, if the value is lower than the threshold, its index will be defined as an array index of the particle. These indexes are called “separation index.” These indexes are sent to index selector. In this function, Doppler frequency in each window is classified to two group by pointing of the separation index; bubble and particle Doppler frequencies as shown in equation (11) and (12). Then, these Doppler frequencies are separately averaged in each group by using equation (13) and (14) for the bubble and the particle respectively. The Doppler frequency of bubble and particle in same measurement channel are known separately. Finally, velocity value for both liquid and bubble are separately calculated in the velocity calculation section.

3. Experimental setup

3.1. Experimental apparatus

Figure 4 shows a schematic diagram of the experimental apparatus in this study. The measurement systems consisted of ultrasonic pulser/receivers, 4 MHz ultrasonic transducers, digitizer, and computer. The detail of UVP system is shown in table 1 respectively. The pulser/receivers emitted and received ultrasonic pulses through an ultrasonic transducer. The echo signals received by pulser/receiver was converted to a digital signal by a digitizer, with a sampling rate of 100 MS/s. The digitizer was connected to a computer. The digitizer and the pulser/receivers were connected and synchronized to each other. The data from digitizer was sent to the computer and analyzed using LabVIEW software. The measurement test section was a vertical pipe made of acrylic with an inner diameter ($D$) of 20 mm. The transducer was installed on the outer surface with an incident angle ($\theta$) 45°. The measurements were conducted in downstream at a distance of 50 $D$ from a bubble injector. Nylon tracer particles with the size of 80 $\mu$m were dispersed in the water. The water temperature was monitored using a thermocouple, and it was controlled around 20 ± 2°C by the cooling coil. The air was injected from bubble injector using an air compressor. The measurement accuracy of liquid phase velocity was evaluated by making a comparison with an electromagnetic flow meter (EMF) (accuracy: ± 0.5% of reading). The comparison was done by using flow rate value. Also, bubble velocity measurement was compared with image processing method which calculates bubble velocity from bubble images were caught up by a high-speed camera (HSC).

Table 1. The equipment list of UVP system.

| Parameter              | Configuration                                      |
|------------------------|----------------------------------------------------|
| Transducer             | 4 MHz with beam diameter 5 mm, Imasonic, model: 0902 0119 |
| Pulser-receiver        | Met-Flow, Model: UVP-DUO                          |
| Digitizer              | National Instrument, Model: NI USB 5133            |
| Operating software     | National Instrument, LabVIEW 2011                 |
| Computer               | Laptop, VAIO                                       |

3.2. Experimental procedure

There were two experiment configurations in this study. Firstly, evaluation of the performance of FFT-based frequency estimator in single-phase liquid flow. The accuracy of the technique was compared with other techniques such as Autocorrelation [9] and Maximum Likelihood Estimation [10]. The experiment was conducted with single-phase liquid (water) at flow rate 3 L/min and 6 L/min. Secondly, the experiment was conducted to measure velocity profile of bubble and liquid in the two-phase bubbly flow. Proposed FFT was applied to distinguish bubble and liquid velocity, and to estimate bubble
diameter and a number of bubble data respectively. The bubbles diameter size in this experiment was about \(0.5 \sim 4\) mm. Experimental conditions and parameter of UVP system are shown in table 2 and table 3 respectively.

![Schematic of the experimental apparatus.](image)

**Figure 4.** Schematic of the experimental apparatus.

**Table 2.** Experimental conditions.

| Parameter                  | Condition                        |
|----------------------------|----------------------------------|
| Fluid                      | Water                            |
| Fluid temperature          | \(20^\circ C \pm 2^\circ C\)     |
| Fluid flow rate            | 3 L/min and 6 L/min              |
| Reynolds number            | 3,169 at 3 L/min \(\sim\) 6,339 at 6 L/min |
| Particle type              | Nylon particle                   |
| Particle size              | 80 \(\mu\)m                      |
| Bubble diameter            | 0.5 \sim 4\) mm                  |
| Pipe size (inner diameter) | 20 mm                            |
| Pipe material              | Acrylic resin                    |
Table 3. Parameter configuration of the UVP system.

| Parameter                  | Configuration |
|----------------------------|---------------|
| Basic frequency            | 4 MHz         |
| Pulse repetition frequency | 8 kHz         |
| Number of repetition       | 128           |
| Channel width              | 0.74 mm       |
| Measurement channel        | 38 channel    |
| Sound velocity in water    | 1,480 m/s at 20°C |
| Number of windows (Wₙ)     | 4             |

4. Results and Discussion

4.1. Comparison of Doppler frequency estimation techniques

Figure 5 shows a comparison of velocity profile measurement with different Doppler frequency estimators. The graph shows the average data of 1,000 instantaneous velocity profiles. The experiment was conducted using single-phase liquid flow at flow rate 3 L/min and 6 L/min. The accuracy evaluation of each technique is shown in table 4. Good agreement is obtained between FFT-based frequency estimator and other techniques (Autocorrelation and Maximum Likelihood estimation (MLE)). Figure 6 illustrates standard deviation value of each technique. The standard deviation for both FFT-based frequency estimator and autocorrelation shows a similar trend. However, the standard deviation in MLE is scattered in particular position, especially at the near and far wall. It means that FFT-based frequency estimator and autocorrelation are better than MLE. Therefore, it can be concluded that performance of FFT-based frequency estimator, at least to be equal and is not worse than other well-known techniques.

Table 4. Measurement result and accuracy of average single-phase liquid velocity profile (1,000 profiles) at 3 L/min and 6 L/min in each Doppler frequency estimation techniques.

| EMF  | FFT | Autocorrelation | MLE |
|------|-----|-----------------|-----|
| Flow rate (L/min) | Flow rate (L/min) | Accuracy (% of reading) | Flow rate (L/min) | Accuracy (% of reading) | Flow rate (L/min) | Accuracy (% of reading) |
| 3 L/min | 3.009 | 0.30 | 2.775 | 7.50 | 2.458 | 18.06 |
| 6 L/min | 5.738 | 4.36 | 5.484 | 8.60 | 4.721 | 21.31 |

Figure 5. Measurement result of average single-phase liquid velocity profile (1,000 instantaneous profiles) at (a) 3 L/min and (b) 6 L/min in each Doppler frequency estimation techniques.
4.2. Separation of two-phase bubbly flow velocity
The second experiment was carried out in the two-phase bubbly flow condition. The bubbles dispersed into the liquid water through bubble injector as shown in figure 4. Figure 7 shows the result of the instantaneous velocity profile which is measured using FFT-based frequency estimator (without separation), henceforth, it is called as “Original FFT” and our proposed technique, it is called as “Proposed FFT.” It can be seen that the instantaneous velocity profile of liquid and bubble is obviously separated when Proposed FFT technique is applied. Instantaneous bubble velocity measurement of the Proposed FFT technique is evaluated by separation velocity profile of bubbly flow. In figure 7(a), at 3 L/min, there are two moving bubbles appear at measurement distance 3~4 mm and at 13~14 mm and their diameter is approximately 2 mm. Their velocity is about 0.228 m/s and 0.292 m/s respectively. In figure 7(b), at 6 L/min, two moving bubbles obviously appear at measurement distance 5~7 mm and at 15~17 mm and their diameter is about 3 mm. Their velocities are about 0.396 m/s and 0.350 m/s respectively. The bubble rise velocity measurement of UVP-Proposed FFT was experimentally compared with the measurement result of Image processing method by the average of 100 bubble velocity. The comparison was specified at bubble diameter about 0.5~1 mm and 2~3 mm and was only demonstrated in far wall region (at position 15~20 mm of measurement distance inside the pipe).

Figure 7. Instantaneous velocity profile of two-phase bubbly flow with separation and without separation; (a) at 3 L/min, (b) at 6 L/min.

Table 5 shows that measurement result of bubble velocity for both systems. The discrepancy is 5.55% at flow rate 3 L/min and 10.95% at 6 L/min when the bubble diameter is about 0.5~1 mm. On the other hand, the discrepancy increases to 34.50% at flow rate 3 L/min and 19.89% at 6 L/min when bubble
diameter is about 2~3 mm. Furthermore, it is confirmed that the bubble velocity changes relative to the bubble diameter; bubble velocity increases as increasing the bubble diameter.

Table 5. Comparison of average bubble velocity measurement (100 value) at far wall zone (position 15~20 mm of measurement distance inside the pipe) between the UVP using the Proposed FFT and the image processing method.

| Bubble diameter | Method       | 0.5~1 mm | Discrepancy | 2~3 mm | Discrepancy |
|-----------------|--------------|----------|-------------|--------|-------------|
|                 | UVP          | Image    |             | UVP    | Image       |
| Flow rate 3 L/min | 0.210 m/s   | 0.222 m/s| 5.55 %      | 0.247 m/s| 0.350 m/s| 34.50 %     |
| Flow rate 6 L/min | 0.308 m/s   | 0.276 m/s| 10.95 %     | 0.344 m/s| 0.420 m/s| 19.89 %     |

In the original FFT, liquid and bubble distribution in the bubbly flow cannot be separated instantaneously. It means that the separation technique is needed. Therefore, without separation technique, the behavior of bubble distribution is not obtained by original FFT. Moreover, because bubble motion cannot be obtained instantaneously, a measurement result in liquid-phase is calculated inaccurately due to bubble data is remained in the raw velocity profile data. Nonetheless, the Proposed FFT measure liquid and bubble velocity instantaneously, and it can distinguish two-phase bubbly velocity profile. Therefore, the velocity profile of liquid-phase is calculated accurately due to the bubble data is removed in the raw velocity profile data.

Figure 8. Comparison of 1000 average liquid velocity profile between the Proposed FFT (separated profile) and the Original FFT (without separation).
Table 6. Accuracy evaluation of liquid velocity profile measurement in two-phase bubbly flow at 3 L/min and 6 L/min.

| Flow rate (L/min) | Flow rate (L/min) | Accuracy (% of reading) | Flow rate (L/min) | Accuracy (% of reading) |
|------------------|-------------------|-------------------------|-------------------|-------------------------|
| 3 L/min          | 3.547             | 18.23                   | 3 L/min           | 3.176                   |
| 6 L/min          | 6.372             | 6.20                    | 6 L/min           | 5.753                   |

Figure 8(a) and table 6 shows a comparison of liquid-phase velocity profile measurement between the Original FFT and the Proposed FFT. It can be summarized that the accuracy of the result that obtained from Proposed FFT after separation is better than the Original FFT both at the flow rate 3 L/min and 6 L/min. Moreover, the standard deviation of the Original FFT is higher than the value of the Proposed FFT at near wall and far wall zone especially as shown in figure 8(b) and 8(c). It can illustrate that the measurement uncertainty by using the Original FFT is higher than the Proposed FFT.

4.3. Number of bubble data

When bubble velocity, bubble diameter, and their position are estimated, it is possible to obtain a number of bubble data along the measurement line. Figure 9 illustrates the number of bubble data, which is obtained from 1,000 bubble velocity profiles after separation. At the flow rate of 3 L/min, the number of bubble data at the far wall region is higher than other zones. It can be interpreted that most of the bubble passes through the far wall zone. At flow rate 6 L/min, the number of bubble data appears on both near wall and far wall zone significantly. It can be concluded that most of the bubble passes through both near wall and far wall regions. In this experiment, the range of bubble diameter was 0.5~4 mm, which is categorized to be a small bubble, it can be summarized that most of the small bubbles existed in the region that is near to a pipe wall. This result also has similarity with the previous study [11].

![Figure 9. A number of bubble data at flow rate 3 L/min and 6 L/min.](image)

5. Conclusion

FFT-based technique collaborated with Windowing and Signal Enveloping for measuring two-phase bubbly flows was proposed. The measurement system employed 4 MHz transducer and Doppler pulse repetition method that was modified by proposed technique for measuring liquid and bubble velocity distributions. This technique analyzes the behavior of Doppler signal (frequency and amplitude), which are reflected by small particle and bubble. The main advantage of this method was not only liquid, and bubble velocity distributions could be obtained separately, but also this method was capable of acquiring the simultaneous of two-phase velocity at same measurement channel. Furthermore, only one resonant frequency was required. Therefore extra equipment was not a necessity. The performance of FFT-based frequency estimator was experimentally compared with other signal processing techniques for the measurement of the velocity profile in the single-phase (liquid) flow. From the result, it was confirmed
that FFT showed a good agreement with other techniques. In bubbly flow, the velocity profile of liquid and bubble was obtained separately. The evaluation was done in the both liquid and bubble phases. Firstly, liquid velocity profile was verified with an electromagnetic flow meter. Secondly, bubble distribution was compared with the image processing method. It was confirmed that the proposed technique could separate both liquid and bubble distributions and the velocity data had a good agreement with another instrument. Moreover, number of bubble data were estimated experimentally. Practically, the diameter of the measured bubble must be smaller than the active diameter of the transducer. The active diameter of 4 MHz ultrasonic transducer is 5 mm, therefore, the maximum size of the bubble that system could detect is limited. The bubble should be smaller than 5 mm. As this limitation, future work should focus on applying lower basic frequency with bigger active diameter transducer to extend maximum limit of bubble diameter.

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