De-aliasing of ultrasonic velocity profiler on bubbly flow beyond the Nyquist limit

Wongsakorn Wongsaroj, Natee Thong-un, Naruki Shoji, Hideharu Takahashi and Hiroshige Kikura

1Department of Mechanical Engineering, School of Engineering, Tokyo Institute of Technology, 2–12–1, Ookayama, Meguro-ku, Tokyo, 152–8550 Japan
2Department of Instrumentation and Electronics Engineering, Faculty of Engineering, King Mongkut’s University of Technology North Bangkok, 1518 Pracharat 1 Road, Wongsawang, Bangsue, Bangkok 10800 Thailand
3Laboratory for Advanced Nuclear Energy, Institute of Innovative Research, Tokyo Institute of Technology, 2–12–1–N17 Ookayama, Meguro-ku, Tokyo, 152–8550 Japan

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1. Introduction

Two-phase bubbly flow is a fundamental phenomenon occurred in several industrial sectors especially in the nuclear reactors. Practically, in the Boiling Water Reactor (BWR), the phenomenon influences the operations of the reactor. In order to operate the reactor effectively and safely, the behaviour of bubbly flow is necessary to be understand. The experimental work is required to clarify flow behavior. Usually, the task has been executed on the channel or pipe. The velocity distribution of the bubbly flow; bubbles and liquid phases is mainly important parameter affects the phase distribution which strongly influence the safety aspect. Hence, it is necessary to be known accurately. Consequently, the measurement technique to measure and distinguish the velocity distribution of bubble and liquid on bubbly flow is needed. Several measurement techniques have been applied to measure the velocity profile in bubbly flow such as Particle Image Velocimetry (PIV). The measurement suddenly fails if the measuring fluid is not clearly transparent. An X-ray method can overcome some of the weakness of the PIV. Nevertheless, the technique requires a special configuration. However, the measurement error of both techniques occurs as bubbles overlapping on the image. The Ultrasonic Velocity Profiler (UVP) method [1] is proposed in this study. It is a non-invasive measurement. Transparency of test section and fluid is not required. The measurement region is in volume line form along with the measurement depth. Hence, the bubble overlapping problem has not much affected. This technique has been applied for the measurement in many fields of fluid mechanic such as velocity profile, flow rate measurement and so on. The UVP measurement is an ultrasound-based technique which can obtain the velocity profile of fluid. Its principle is based on the utilization of ultrasonic reflection. Figure 1 illustrates the UVP configuration and velocity profile reconstruction. An ultrasonic pulse is transmitted from the transducer along the measurement line to the fluid. The echo signal reflected from moving reflector such as small particle dispersed in the fluid is derived by the same transducer. When the ultrasonic pulse is emitted repeatedly, the echo signals is obtained sequentially. Doppler signal influenced by the velocity of moving particle can be demodulated from the echo signals. The Doppler frequency \( f_D(i) \) directly relates to the velocity of the particle \( V(i) \) is velocity at that position. Hence, the velocity of the particle at position \( V(i) \) can be computed as

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

Where \( c \) is sound velocity in fluid, \( f_0 \) means center frequency of ultrasonic pulse and \( \theta \) is incident angle. The velocity profile along the measurement line can be reconstructed if particles are sufficiently dispersed. However, the original UVP can perform only in the liquid flow. In the bubbly flow, Aritomi et al. [2] proposed the UVP collaborated with the statistical method to classify the velocity profile of the bubble and liquid in bubbly flow. The separation was limited when velocity of both phases is similar. The multiwaves technique [3] was employed to measure and separate bubble and liquid velocity profiles. Nevertheless, this technique required double equipment and special transducer due to two frequencies concept. In order to minimize these limitations and complexity. The UVP on single frequency had been focused. Basically, the Doppler amplitude reflected from a bubble is larger than the amplitude obtained from a particle. Besides, Doppler frequencies of both reflectors are not similar due to their velocity. Hence, multifrequency and difference of amplitude on the Doppler signal are observed. Based on this behaviour, the UVP with phase separation algorithm [4] to obtain the velocity profile of the bubble and liquid separately was proposed. The idea is applying of the integration of Short-Time Fourier Transform (STFT) and Doppler amplitude classification into the UVP to reconstruct velocity of both phases. This algorithm utilizes only single frequency. Hence, simple equipment and commercial transducer can be employed. Also, the velocity of both phases can be separated even at a similar value. However, in the normal operation of BWR, the velocity value of both phase on the reactor core is above 1 m/s. Hence, the experimental measurement must be performed on this condition. The UVP measurement on the
channel or pipe, the incident angle at 45 degrees is preferred because the transmission ratio is maximum, no two-wave mode and high measurement sensitivity [5]. The maximum measurable velocity \( V_{\text{max}} \) (Nyquist velocity) of the UVP is limited by the Nyquist limit considering pulse repetition frequency \( f_{\text{PRF}} \) as the sampling rate as represent in Eq. (2). The required velocity range is higher than the maximum velocity of the UVP. The aliasing of velocity profile occurs obviously [5].

\[
V_{\text{max}} = \frac{c f_{\text{PRF}}}{4 f_0 \cos \theta}
\]  

(2)

Although the decreasing of \( f_0 \) and the increasing of \( f_{\text{PRF}} \) can increase the limit of \( V_{\text{max}} \), these altering cause low spatial resolution and small measurement depth. Therefore, de-aliasing technique has been required. Murakawa et al. [6] proposed the dual PRF method with moving averages to measure velocity profile of the water at high flow rate. Then, Shoji et al. [7] employed UVP with wideband phase difference method to obtain velocity profile of liquid beyond Nyquist velocity level. However, these techniques have been not applied in the bubbly flow.

In this study, the UVP with phase separation algorithm was combined with cross correlation method, which is called Developed-UVP in this study, to obtain the velocity profile of bubble and liquid at beyond the Nyquist limit. This study focuses on the extension of the velocity range only one time beyond the Nyquist limit.

2. Measurement technique

The phase separation technique is integrated with cross correlation function for the operation in the UVP system to obtain the velocity in the bubbly flow at beyond the maximum limit. It is called Developed-UVP in this study. Figure 2 illustrates the process of proposed algorithm. Firstly, the Doppler signal \( D(n) \) (discrete data) is extracted from the echo signals as shown in Eq. (3) obtained from transducer and pulser/receiver respectively. The extraction is processed by quadrature demodulation [5].

\[
D_{n}(n) = A_{n} \cos \left( \frac{2 \pi n f_{0} \phi}{f_{\text{PRF}}} - \varphi \right) - j A_{n} \sin \left( \frac{2 \pi n f_{0} \phi}{f_{\text{PRF}}} - \varphi \right)
\]  

(3)

where \( n \) represents sampling rate of Doppler signal along number of repetition \( N_{\text{REP}} \), \( A \) is the amplitude, and \( \varphi \) is the initial phase. Then, the Doppler signal is sent to STFT to derive time-frequency spectrogram of signal. The calculation is expressed in Eq. (4) and the energy density of spectra at time \( k \) is denoted by Eq. (5). Time-frequency resolution depends on time step \( S_{n} \) and window length \( W_{n} \). The spectrogram is sent to the peak detector for analyzing the energy peaks of the spectrogram. Peak value in each position informs the Doppler frequency data \( f_{D} = [f_{D1}, f_{D2}, \ldots, f_{Dn}] \) and time location \( \tau = [t_1, t_2, \ldots, t_m] \).

\[
X(k, f_{D}) = \sum_{n=0}^{N_{\text{REP}}-1} D(n)W_{n}(n - kS_{n}) \exp(-jn2\pi f_{D})
\]  

(4)

\[
P(k, f_{D}) = |X(k, f_{D})|^2
\]  

(5)

The selected amplitude data is then compared with a threshold value. The value is defined as being higher than the maximum Doppler amplitude of the particle and lower than the Doppler amplitude obtained from the bubble. The amplitude index is classified into the index of bubble and liquid. When the amplitude value is higher than the threshold, the index is defined as a bubble index \( (i_{b} = [i_{b1}, i_{b2}, \ldots, i_{bn}]) \). Secondly, when the value is lower than the threshold, the index is expressed as a particle index \( (i_{p} = [i_{p1}, i_{p2}, \ldots, i_{pm}]) \). Doppler frequency data analyzed by peak detector is classified by these amplitude indexes to be Doppler frequency of bubble group \( f_{D_{\text{bubble}}}[f_{D_{\text{bubble}}, f_{D_{\text{bubble}}, \ldots}}, f_{D_{\text{bubble}}}] \) and particle group \( f_{D_{\text{particle}}}[f_{D_{\text{particle}}, f_{D_{\text{particle}}, \ldots}}, f_{D_{\text{particle}}}] \). The Doppler frequency in each group is averaged. Hence, the Doppler frequency of bubble \( f_{D_{\text{bubble}}} \) and particle \( f_{D_{\text{particle}}} \) in the same measurement channel is decomposed apparently. Consequently, the velocity of the bubble and particle (liquid) can be calculated simultaneously. Besides, the cross correlation function and peak detector as shown in Eqs. (6) to (7) which is efficient time delay estimator used to determine the time shift \( \tau_{n} = \ldots \)
where $R$ is cross-correlation function, $n$ is number of echo, $N_S$ represent sample length and $k$ is discrete data of cross-correlation function. The time shift is calculated until $n = N_{REF} - 1$. Then, the time shifts affected by the bubble and the particle is classified by amplitude index of each group ($i_{\text{b}}, i_{\text{p}}$). The time shift value in array form of each group $\tau_{i,\text{bubble}} = [\tau_{i,\text{b1}}, \tau_{i,\text{b2}}, \ldots, \tau_{i,\text{bN}}]$ and $\tau_{i,\text{particle}} = [\tau_{i,\text{p1}}, \tau_{i,\text{p2}}, \ldots, \tau_{i,\text{pN}}]$ is averaged. Consequently, the time shift value of bubble and particle $\tau_{i,\text{bubble}}$ and $\tau_{i,\text{particle}}$ is distinguished separately. The folding number $w$ which used to solve the aliasing problem of the velocity value can be computed by comparing the time shift in each phase with the Nyquist value (at $\pi$). Folding number is equal 0 if $\tau$ is lower than the Nyquist value. In the contrary, if $\tau$ is higher than Nyquist value, folding number will be defined to be 1. The true velocity of both phases $V_{\text{true, bubble}}$ which is higher than Nyquist velocity can be de-aliased from Eq. (8).

3. Experimental setup

The performance of the Developed-UVP is demonstrated by the experimental measurement. The experiment was performed on vertical pipe flow apparatus with co-current bubbly flow. The experimental setup is shown in Fig. 3. Working fluid was tap water which was dispersed by nylon particle 80 µm. Its temperature was controlled around 20 ± 2 degree Celsius. In the test section, the inner diameter of the acrylic pipe was 20 mm and thickness was 1 mm. It located downstream from a bubble generator with a distance of 50 D. The air was supplied to bubble generator for generating the bubble. In the experiment, the UVP system consisted of a 4 MHz ultrasonic transducer (Model: TX-4.5-8, MFG: MET-Flow, Switzerland), a Pulser/Receiver (Model: RPR-4000, MFG: RITEC, USA), Function generator (Model: AFG-31051, MFG: RSPRO, UK), a Digitizer which the sampling speed is 100 MS/s (Model: NI USB 5133, MFG: NI, USA) and a computer with LabVIEW program 2011. The emission wave is set at $f_0 = 4$ MHz with the 4 cycles per pulse and the voltage $150 \text{V}_{\text{p-p}}$. It emitted at $f_{\text{REP}} = 8$ kHz which has number of repetitions $N_{\text{REF}} = 128$. The receiving gain is 45 dB. The spatial resolution is 0.74 mm. The transducer was installed at incident angle 45 degree. Therefore, the Nyquist velocity is 1,024 mm/s.

4. Result and discussion

4.1. Measurement at below Nyquist limit

First of all, the experiment was conducted to measure the velocity profile on bubbly flow below Nyquist velocity. The superficial liquid velocity $U_L$ was set at 300 mm/s. The superficial gas velocity $U_G$ was set at 5.3 mm/s. The bubble diameter is approximately ≈2−3 mm. In previous study [4], the performance of Developed-UVP that exclude de-aliasing was verified reasonably by comparing with the PIV method. The discrepancy of the evaluation is inside ±15%. Figure 4(a) shows the results of averaging data of 2,000 instantaneous velocity profile in bubbly flow. The horizontal axis indicates the distance from the wall ($r$) normalized by the pipe radius ($R$). The measurement results of Developed UVP with de-aliasing were compared with the result of without de-aliasing. Figures 4(b) and 4(c) illustrate the discrepancy of the comparison. The deviation of the comparison in each phase was mostly within the acceptable range of ±5%.

4.2. Measurement at beyond Nyquist limit

In order to confirm the performance of Developed-UVP for the measurement beyond Nyquist limit, the experimental measurement was executed to obtain the velocity profile on bubbly flow at the velocity level was higher than Nyquist velocity (> 1,024 mm). The $U_L$ was set at 1,300 mm/s. The $U_G$ was set at 5.3 mm/s. Figure 5(a) shows the average velocity profile (2,000 instantaneous data). The aliasing problem could be observed when de-aliasing function was not employed in the Developed-UVP. Clearly, after apply de-aliasing algorithm, the aliasing of velocity profile was solved. The velocity profile at above the Nyquist velocity was derived. The similarity of the velocity level of both phases could be observed. It is reasonable due to less of buoyancy effect that influenced by smaller bubble diameter and high influence of liquid drag force when compare to the case at low $U_L$. Figure 5(b) represents the unsuccessful rate of de-aliasing.
on the measurement. This data was calculated from the instantaneous velocity data that be failed of de-aliasing which was normalized by the number of profiles (The failed data used for calculation was the instantaneous velocity at still has aliasing after de-aliasing process had been executed). The unsuccessful rate of de-aliasing mostly was lower than 1% except only at near-wall region which was interfered by the overlapping region between fluid and pipe wall. Hence, it can be summarized that Developed-UVP with de-aliasing algorithm has applicability to obtain the velocity profile of bubble and liquid in the bubbly flow even beyond the Nyquist limit.

5. Conclusion

The UVP with phase separation technique was combined with cross correlation method for the measurement of velocity profiles of bubble and liquid in bubbly flow beyond the Nyquist velocity which is called Develop-UVP in this study. The system employed the time frequency analysis and Doppler amplitude classification to classify information of both phases. Furthermore, the time shift between the repeatedly obtained echoes of both phase was used to de-aliasing the velocity profile of bubble and liquid at higher than the maximum limit. The experiment was conducted on vertical pipe flow apparatus. The measurement applicability of Developed-UVP was demonstrated experimentally on bubbly flow at below and beyond the Nyquist limit.

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