Development of a Hybrid Ultrasonic Flow Meter With the Use of Pulsed Doppler and Time-of-Flight

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The time-of-flight ultrasonic flow meter (TOF) derives flow rate from line-average velocity based on transit time of ultrasonic pulse on the ultrasonic path. Hence, accuracy of the TOF is strongly influenced by the velocity profile in a pipe. On the other hand, the ultrasonic pulsed Doppler method (UDM) enables to derive the flow rate from the velocity profile. Therefore, it does not require the profile factors (PFs). Hybrid ultrasonic flow meter between TOF and UDM is useful for on-site calibration for determining the profile factor. However, the UDM has relatively large uncertainty in comparison to TOF. Despiking method is useful to eliminate the uncertain data as a post-processing. In this study, a method to eliminate the uncertain velocity profiles was proposed. Line-average velocities were obtained using TOF and UDM simultaneously, and these were compared to eliminate the scattering data. As a result, it was shown that the hybrid ultrasonic flow meter made possible to determine the PF under asymmetrical flow condition. The PFs obtained for the symmetrical and asymmetrical flows were in good agreement with the calibration results of the reference flow meter. The error could be reduced to ±1% of the flow rate

Keywords: Hybrid ultrasonic flow meter, Time-of-flight, Profile factor, Despiking method

1. Introduction

Time-of-flight ultrasonic flow meter (TOF) has been widely applied in industrial field due to its advantages, such as small pressure loss, applicability to large diameter pipe. The TOF derives flow rate from the difference of the transit time of ultrasonic pulse which depends on the line-average velocity on ultrasonic path. Hence, the profile factors, PFs, to convert the transit time to the flow rate are required. The PFs are calibrated before shipment of the flow meter under the ideal flow conditions. However, there is a demand to calibrate the PFs at on-site because accuracy of the flow meter might change owing to the aging effect.

On the other hand, the ultrasonic pulsed Doppler method (UDM) enables to derive the flow rate from the velocity profile. Therefore, it does not require the PFs. Even if velocity profile in the pipe is distorted, flow rate can be obtained accurately using multiple measuring lines [1]. However, the UDM requires ultrasonic reflectors in the flow, and it is difficult to use the UDM usual. Hence, a hybrid ultrasonic flow meter which calibrates TOF by using UDM has been proposed [2]. Because maximum detectable velocity of the UDM was limited by the Nyquist sampling theorem, the hybrid ultrasonic flow meter could be applied only for low flow-rate conditions. Authors developed a dealiasing method, namely, the feedback method for measuring higher flow rate and six times higher flow rate could be measured [3,4].

The uncertainty of velocity measurement becomes worse with increasing the maximum measurable velocity using the feedback method. If the velocities are not accurately obtained, spike data appears in the velocity distributions. In order to eliminate the spike data, despiking methods have been developed [5].

In this study, in order to improve the average velocity profile for the UDM, despiking method was applied for the feedback method. Furthermore, a hybrid system with UDM and TOF was applied for eliminating the uncertain data for calculation of the average velocity profile.

2. Measurement uncertainty and despiking method

2.1 Spike velocity

Feedback method [3] is based on difference between the phase shifts between the echo signals. In the calculation, the higher signal-to-noise ratio is required for obtaining the velocity profile accurately in comparison to the conventional UDM, *i.e.* single pulse repetition frequency, PRF. Further, the measurement volume is important as well. If the measurement volume is not large enough to allow consideration of the moving distance of a reflector during the pulse emission period, the velocity cannot be correctly determined.

Figure 1 shows an example of reliable and noised instantaneous velocity profiles. Feedback method was applied for measuring higher velocity under distorted velocity condition. If reflectors are not enough or not appropriately distributed on the ultrasonic path during the measurement, it can be found that some velocities are not correctly obtained. These velocities are called as spike velocities.

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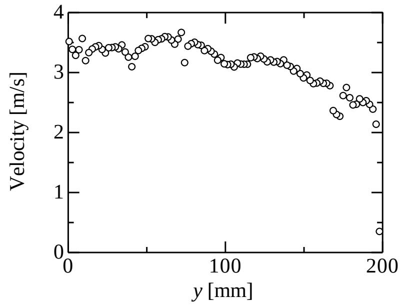
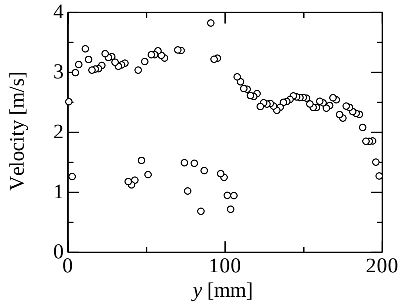


(a) Reliable velocity profile



(b) Noised velocity profile

Figure 1: Instantaneous velocity profile measured using Feedback method under distorted flow condition.

2.2 Despiking method

Figure 2 shows an example of time-series of velocity data at a measurement position. It can be confirmed that it includes some spike data, *i.e.* error data. To detect the spike data, despiking methods have been developed. Here, we employ Goring and Nilora's method [5]. They proposed the phase-space thresholding method. It is based on the differentiation of the high frequency components of a signal in three-dimensional phase space.

Examples of the relation between the velocity data in phase space are shown in Figure 3. v is the velocity, Δv is the derivative of v and $\Delta^2 v$ is the second derivative of v. The solid line of ellipsoidal represents the threshold in each phase. Velocities outside the thresholding are considered as spike data. Some data appears at position where far from the center region. These data represent that the Nyquist holding number is wrongly evaluated. Thus, velocities discretely appears $v \pm n v_{max}$, where n is the Nyquist holding number and v_{max} is the maximum measurable velocity.

Figure 2 also shows the spike data. For removing the spike data, uncertainty of the statistical error can be improved. The despiking method is useful for evaluating the flow properties. However, this method is post-processing and is difficult to evaluate at short times and on-time measurement.

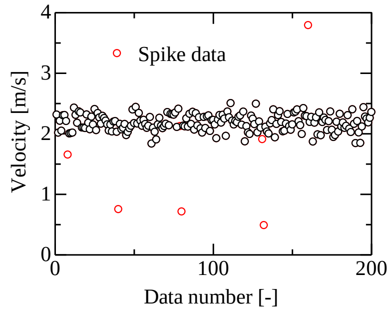


Figure 2: Time-series of velocity data.

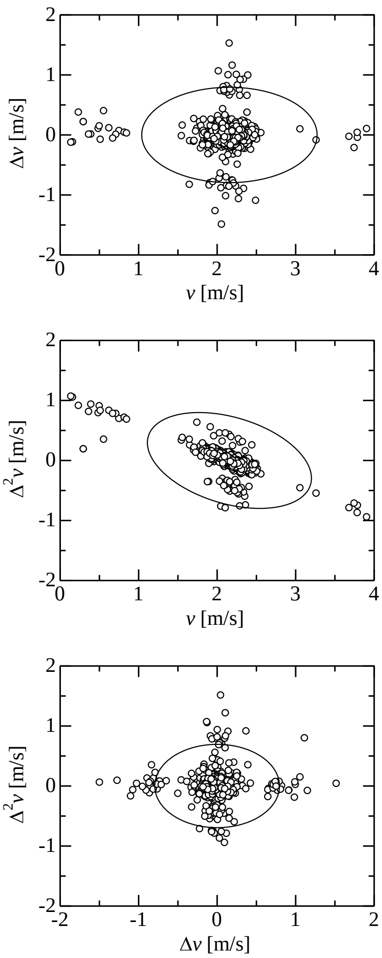


Figure 3: Phase-space thresholding method for evaluating the spiked velocities. Ellipsoidal represents the threshold, and velocities outside the thresholds are considered as spiked data.

3. Hybrid ultrasonic flow meter

3.1 Transit-time measurement

To evaluate uncertainty of velocity profile as well as the flow rate, hybrid ultrasonic measurements of time-of-flight (TOF) and UDM was developed.

Figure 4 shows the measurement principle of the TOF. A pair of ultrasonic transducers is installed with inclination angle, θ, on the pipe wall; t represents the transit time of an ultrasound signal between transducers in stagnant flow. If the ultrasonic pulse is emitted from the upstream transducer, the transit time is shortened to $t - \Delta t$ by the flow velocity, whereas the transit time from the downstream transducer is delayed to $t + \Delta t$. The Δt is related to the line-averaged velocity along the measuring line between the sensors, $V_{L,\mathrm{TOF}}$, and the relationship is expressed as

$$V_{L,\mathrm{TOF}} = \frac{c^2}{D\tan\theta}\Delta t \tag{1}$$

As shown in the above equation, the TOF can derive only the line-averaged velocity. In order to evaluate the flow rate, profile factor, PF, is used to convert V_L to flow rate:

$$Q_{\mathrm{TOF}} = PF \cdot \frac{\pi D^2}{4} \cdot V_{L,\mathrm{TOF}} \tag{2}$$

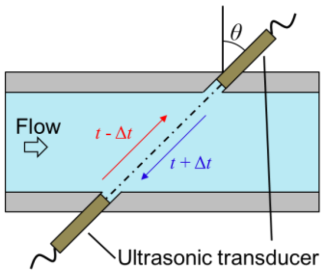


Figure 4: Schematic of time-of-flight measurement.

3.2 Measurement system

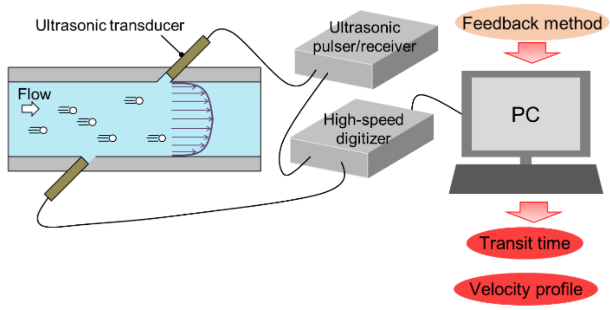
In the hybrid ultrasonic flow meter, UDM is used for measuring velocity profile. By integrating the obtained velocity profile over the cross-sectional area of a pipe, the flow rate, Q, can be calculated. Using Q, the PF can be determined as

$$PF = \frac{Q}{V_{L,\mathrm{UDM}} \cdot {\pi D^2}/{4}} \tag{3}$$

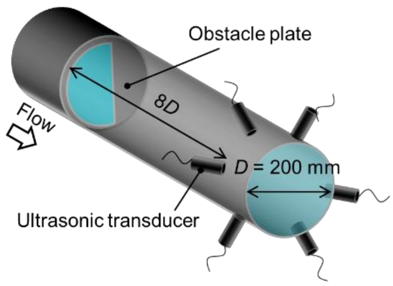
Thus, the PF can be obtained by using the UDM in conjunction with the feedback method. Further, V_L obtained from TOF and the UDM was compared to eliminate the uncertain data. It can be considered that the V_L calculated from the TOF is more accurate than that obtained from UDM. Thus, if V_L differs at more than Ñ5% between TOF and UDM, the velocity profiles were eliminated for the flow rate calculation.

The developed measurement system is schematically shown in Figure 5. The system consists of an ultrasonic pulser/receiver (JPR-2CH-KB, Japan Probe Co., Ltd.), a high-speed digitizer (PXI-5114, National Instruments Corp.). The two ultrasonic transducers are connected to the pulser/receiver. One transducer emits ultrasonic pulses and receives echo signals from the reflectors, and the other transducer receives the transmitted ultrasonic pulse. Signals recorded by the digitizer are transferred to the PC. Thus, both the echo and transmitted signals can be simultaneously recorded.

Experiments were conducted at a flow rate calibration facility of National Metrology Institute of Japan (NMIJ) of Advanced Industrial Science and Technology (AIST). Working fluid was water. Figure 6 shows schematic of the test section. Test section was horizontal pipe and its inner diameter, D, was 200 mm. A couple of transducers were set at d = 45Åand submerged into the water. f_0 of the transducers was 1 MHz and its effective diameter was 12 mm. Small air bubbles were injected into the flow as ultrasonic reflector, and a rectifier was installed at upstream of the test section. The distance from the rectifier and the test section was 55D. Installing the obstacle plate at 8D upstream from the test section, flow can become asymmetric. The obstacle plate has a semicircle-shaped aperture and its aperture ratio is 0.66.



Figue 5: Schamatic of the hybrid ultrasonic flow meter.



Figue 6: Schamatic of the test section. An obstacle plate was installed for measuring asymmetrical flow condition.

4. Results and discussion

4.1 Line-averaged velocity

The $V_{L,\mathrm{TOF}}$ and $V_{L,\mathrm{UDM}}$ were compared as shown in Figure 7 under symmetrical and asymmetrical flow conditions at flow rate of 320 m^3/h. Temporal resolutions of UDM and TOF was 69 ms and 0.54 ms, respectively. For direct comparisons, moving average was applied for $V_{L,\mathrm{TOF}}$. Tendencies of $V_{L,\mathrm{UDM}}$ were in good agreement with that of $V_{L,\mathrm{TOF}}$. The velocity fluctuation is more significant at asymmetrical flow than that at symmetrical flow, and the difference of V_L is large at asymmetrical condition. There were some velocities that the difference of V_L between TOF and UDM exceeds 5%. Thus, theses data were eliminated for calculating the averaged velocity profile.

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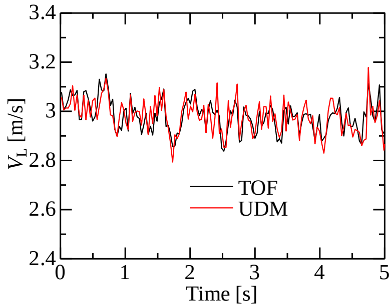
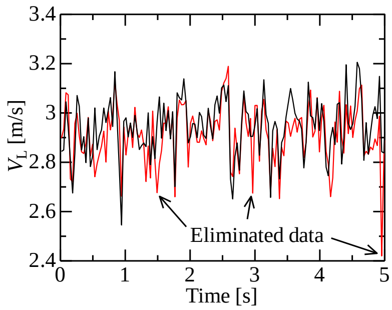


(a) Symmetrical flow



(b) Asymmetrical flow

Figure 7: Simultaneous measurement of V_L in TOF and UDM.

1,000 instantaneous velocity profiles were averaged. For the symmetrical flow, the flow rate was calculated from the velocity profile for one-half region of the pipe. For the asymmetrical flow, the flow rate cannot be derived from a single line measurement. Therefore, multiple velocity profiles were measured along the three measuring lines. Each transducer was used to obtain the velocity profile in one-half of the pipe, and using six transducers, the velocity profiles along the three measuring lines were obtained, as shown in Figure 8.

PFs were determined using Eq. (3) based on the flow rate calculated from the velocity profiles. For averaging the PFs in each flow condition, PFs were determined at 0.948 for symmetrical and at 0.966 for asymmetrical flow conditions as shown in Figure 9. In the asymmetrical flow, the PFs were calculated along each measuring line. The flow rates obtained using the UDM were substituted for Q, and the obtained $V_{L,\mathrm{TOF}}$ values were substituted for V_L in the equation. The PFs under the asymmetrical-flow conditions were higher than those under the symmetrical flow conditions, because V_L for the asymmetrical flow was lower than that for the symmetrical flow. In the asymmetrical flow, the PFs depend on the measuring lines because the velocity profile is different along different measuring lines. The average PFs were determined under the symmetrical and asymmetrical flow conditions for each measuring line by averaging the PFs of each flow rate. The PFs obtained for the symmetrical and asymmetrical flow were in good agreement with the calibration results of the reference flow meter. The error could be reduced to ±1% of the flow rate.

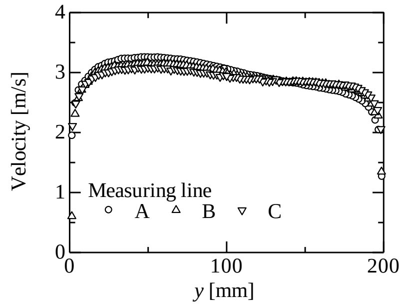


Figure 8: Average velocity profile at Q = 320 m^3/h for asymmetrical flow.

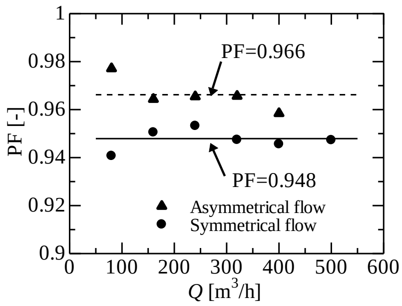


Figure 9: PF in each flow rate under symmetrical and asymmetrical flow conditions. The PFs were determined by the flow rate obtained by using UDM.

5. Conclusions

Hybrid ultrasonic flow meter between TOF and UDM is useful for on-site calibration for determining the profile factor. However, the UDM has relatively large uncertainty in comparison to the TOF. Despiking method was useful to eliminate the uncertain data as a post-processing for the UDM velocity distributions. In this study, a method to eliminate the uncertain velocity profiles was proposed. Line-average velocities were obtained using TOF and UDM simultaneously, and these were compared to eliminate the scattering data. As a result, it was shown that the hybrid ultrasonic flow meter made it possible to determine the PF under asymmetrical flow condition.

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