Improvement in Measurement Volume in Near-wall Region Using Ultrasonic Multi-wave Pulsed Doppler Method for Flowrate Measurement

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The ultrasonic pulsed Doppler method can be applied to obtain the velocity distribution on an ultrasonic beam path. This technique has many advantages. However, the measurement volume is relatively large. In order to clarify the effect of the measurement volume on the velocity measurement accuracy, the beam diameter with different basic frequency, and the channel distance were changed for measuring the velocity profiles. Results indicated that the ultrasonic beam diameter significantly affected the measured velocities in the near-wall region. In order to improve the velocity measurement accuracy in the near-wall region, a multi-wave transducer was proposed for the measurement. The velocity distribution was accurately obtained over the channel by combining the velocity distributions at 8 MHz for the near-wall region and 2 MHz for the region far from the transducer.

Keywords: Measurement volume, Ultrasonic beam diameter, Multi-wave transducer, UVP, Staggered trigger method, Flowrate measurement

1 INTRODUCTION

The ultrasonic velocity profile (UVP) method has many advantages. However, the measurement volume is relatively large compared with those of other flow measurement techniques such as LDV, and this must be carefully considered. Aritomi et al. [1] reported that part of the ultrasonic measurement volume was located within the wall in the near-wall measurement position and that correction of the measurement position was necessary. The region increased with the ultrasonic beam diameter. Therefore, it is opined that smaller measurement volumes are suitable for the UVP measurement. The beam diameter, D_{US}, and ultrasonic basic frequency, f_0, are related: higher f_0 is typically selected for smaller D_{US}. As the f_0 increases, the ultrasonic attenuation in the medium increases, and it is difficult to measure the velocity distributions for a long distance. Furthermore, the maximum measurable velocity decreases with higher f_0. Hence, the f_0 and D_{US} are also considered in selecting the measurement conditions.

In this study, a multi-wave ultrasonic method [2] is employed for measuring velocity profiles. The multi-wave ultrasonic transducer used includes two ultrasonic sensors with different f_0 and D_{US}. The higher f_0 with smaller D_{US} was used for measuring velocity profiles in near-wall region, and the lower f_0 with larger D_{US} was used for measuring velocity profiles far from the transducer. The profiles were combined to determine the velocity over the channel.

2 ULTRASONIC DOPPLER METHOD

2.1 Maximum detectable velocity and measurable length

The maximum detectable velocity, v_{max}, is limited by the Nyquist sampling theorem, and it is defined as

$$v_{\max} = \frac{c f_{prf}}{4 f_0}, \tag{1}$$

where c is the sound velocity and f_{prf} is the pulse repetition frequency (PRF). The maximum measurable length L_{max} is obtained as

$$L_{\max} = \frac{c}{2 f_{prf}} = \frac{cT}{2}. \tag{2}$$

Hence, the v_{max} and the L_{max} are compatible, and the v_{max} increases with decreasing L_{max}.

2.2 Measurement volume and reflector detectability

The measurement volume of the UVP is cylindrical in shape with beam diameter D_{US} and channel width ΔL. ΔL can be controlled by changing the number of cycles in the ultrasonic pulse, N_{pulse}, and it is obtained as

$$\Delta L = \frac{c N_{cycle}}{2 f_0}. \tag{3}$$

The velocity at a position is derived from the phase difference between consecutive echo signals reflected from tracer particles. Hence, the particles are assumed to be in the same measurement volume during the pulse repetition period, T, as shown in Figure 1. If a particle exists in a measurement volume and moves parallel to the flow direction, the maximum velocity required for the particle to remain in the same measurement volume during T, v_{allow}, is determined geometrically as

$$v_{\text{allow}} = \frac{\frac{\pi}{4} D_{\text{US}} \Delta L}{\left(\frac{\pi}{4} D_{\text{US}} \sin\theta + \Delta L \cos\theta \right) \cdot T}. \quad (4)$$

θ is the incident angle of the transducer. If the particle velocity is larger than v_{allow}, the velocity cannot be detected in the UVP. With increasing ΔL, the possibility of obtaining consecutive echo signals from the same particle increases.

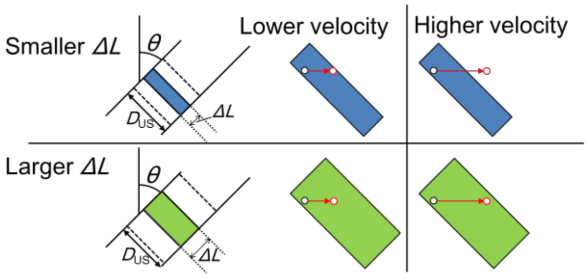


Figure 1: Influence of measurement volume

3 Multi-wave method

3.1 Multi-wave transducer

For maximizing the velocity accuracy in the near-wall region, the D_{US} is must be as small as possible. However, a lower frequency with a large D_{US} must be chosen to measure long distances because of the ultrasonic attenuation. In general, f_0 and D_{US} are related because of the ultrasonic pressure distribution. If an ultrasonic transducer with a small D_{US} and low f_0 emits ultrasonic pulses, the ultrasonic pressure distribution has large divergence. Therefore, a transducer with low f_0 and large D_{US} is desirable. Furthermore, a transducer with a lower f_0 is useful for measuring higher velocities. As a solution to this problem, the multi-wave transducer [2] is proposed for the measurement.

A schematic of the multi-wave transducer is shown in Figure 2. An ultrasonic sensor with a basic frequency of 8 MHz was installed in the center of the transducer. Also, a hollow 2-MHz ultrasonic sensor was installed along the central axis. The inner diameter was 3 mm, and the outer diameter was 10 mm. The sensors were connected using BNC connectors. Hence, both the 2- and 8-MHz ultrasonic beams can be emitted independently.

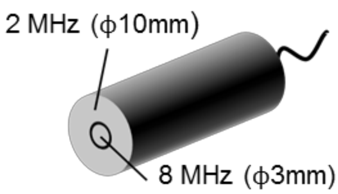


Figure 2: Schematic of the multi-wave transducer

3.2 Experimental method

Experiments were conducted in an acrylic horizontal duct 50 mm in width and 25 mm in height (H). The working fluid was water, and the water temperature was maintained in the range of 18-22 ˚C using a subcooler. Nylon micro particles were seeded in the water as tracers at a density of 0.3 g/l. The specific density of the particles was 1.02 and the average diameter was 120 μm. The multi-wave transducer was set at the outer surface of the top of wall, with θ = 45°. It was submerged in the water to adjust the acoustic impedance.

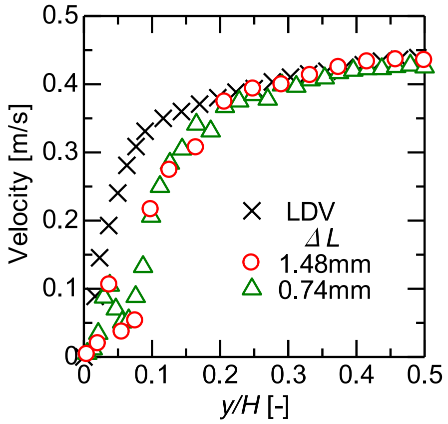
Ultrasonic pulses were emitted by an ultrasonic pulser/receiver and the ultrasonic transducer. The echo signals were recorded using a high-speed digitizer. The pulse repetition frequency was controlled by a function generator. An instantaneous velocity profile was derived from 512 echo signals, and 1,000 instantaneous velocity profiles were averaged. Correction of the measurement position [1] was applied to the near-wall region. Laser Doppler velocimetry (LDV) was used for comparing the velocity with the UVP data.

4 RESULTS AND DISCUSSIONS

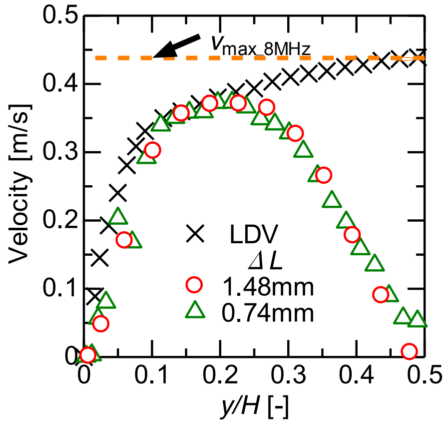
4.1 Same PRF at 2 and 8 MHz

Figure 3 represents average velocity distributions measured using the multi-wave TDX of 2 and 8 MHz. The horizontal axis indicates the distance from the wall surface, and the vertical axis indicates the average velocity converted to the mainstream direction. The flow condition is represented by a Reynolds number (Re) of 12,000. The T (= $1/f_{prf}$) was 0.149 ms.

The measured velocity distribution measured for the 2-MHz beam exhibits large differences between the LDV and the UVP data, particularly in the near-wall region. This region corresponded to the corrected channel position; that is, part of the ultrasonic beam overlapped with the wall. If part of the ultrasonic overlapped with the channel wall, ultrasonic reflections occurred at the solid boundary. These reflections make it difficult to obtain the echo signals from the tracer particles. Consequently, misdetection of the velocity occurred for some of the profiles. With decreasing D_{US}, the region of overlap also decreases. Hence, a better velocity profile could be obtained in the near-wall region with a lower D_{US}. Therefore, a small measurement volume is suitable for measuring the near-wall region. However, the velocity for the 8-MHz beam at 0.2 > y/H differs



(a) 2MHz



(b) 8MHz

Figure 3: Velocity distribution at *Re* = 12,000

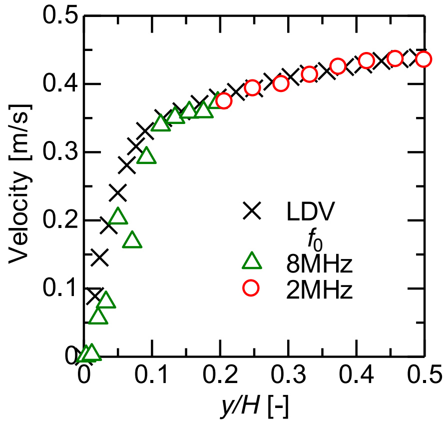
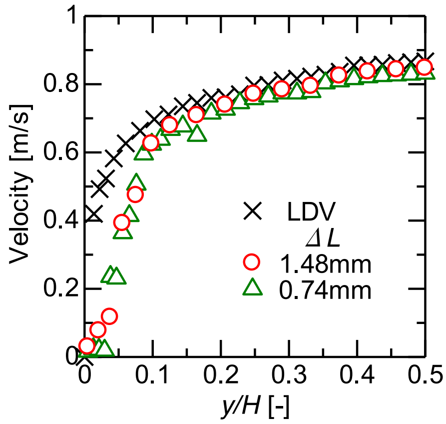


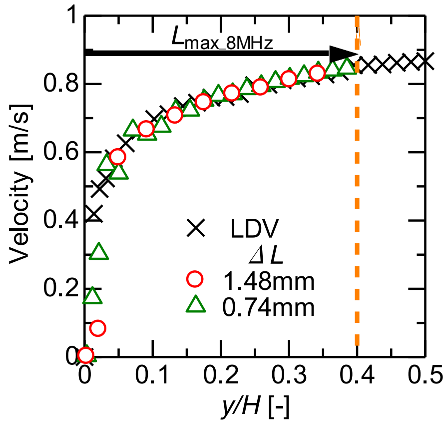
Figure 4: Velocity distribution at *Re* = 12,000

Table 1: v_{allow} at T = 0.149 ms

f_0 [MHz]	ΔL [mm]	v_{allow} [m/s]
2	0.74	6.41
	1.48	11.8
8	0.74	5.34
	1.48	8.61



(a) 2MHz



(b) 8MHz

Figure 5: Velocity distribution at *Re* = 24,000

considerably from the LDV data. This is because of velocity aliasing. As shown in Eq. (1), v_{max} changes with f_0 for a constant f_{prf}. In cases of f_0 = 2 and 8 MHz, the v_{max} with f_0 = 2 MHz, v_{max_2MHz}, is 4 times greater than the v_{max} with f_0 = 8 MHz, as shown in Figure 3(b).

v_{allow} is calculated using Eq. (4) as shown in Table 1. Because v_{allow} is far higher than the flow velocity, the effects of ΔL on the velocities were not significant for any f_0.

By combining the profiles at 2 and 8 MHz, the velocity accuracies over the channels were improved, as shown in Figure 4. In this condition, the profiles were combined at y/H = 0.2.

4.2 Different PRFs at 2 and 8 MHz

Considering that the measurement system can employ different PRFs, T changed with f_0, T_{2MHz} = 0.250 ms, T_{8MHz} = 0.0625 ms. The measurement results at *Re* = 24,000 are shown in Figure 5. Because T_{2MHz} is 4 times larger than T_{8MHz}, v_{max_2MHz} = v_{max_8MHz}. However, owing to the difference in the PRFs, the measurable length of 8-MHz beam was limited at y/H < 0.4.

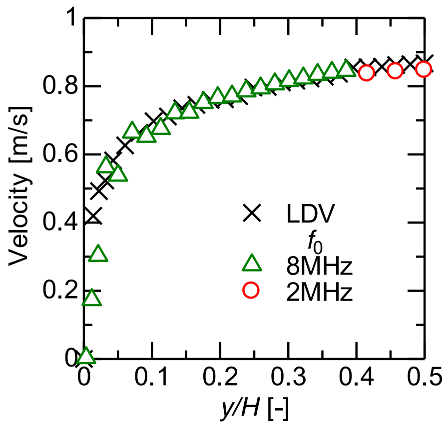


Figure 6: Combined velocity distribution at *Re* = 24,000

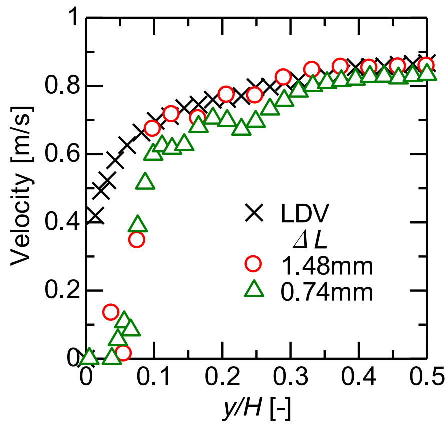


Figure 7: Velocity distribution by staggered trigger method at *Re* = 24,000

Table 2: v_{allow} with different PRFs

f_0 [MHz]	T [ms]	ΔL [mm]	v_{allow} [m/s]
2	0.250	0.74	3.83
		1.48	7.04
8	0.0625	0.74	12.7
		1.48	20.6

Table 3: v_{allow} at $T+T_s$ = 0.150 ms

f_0 [MHz]	ΔL [mm]	v_{allow} [m/s]
2	0.74	0.638
	1.48	1.17

In the case of the 8-MHz beam, the velocity distributions agree well with the LDV data. Table 2 presents the relation of the v_{allow} in each condition.

It can be confirmed that the v_{allow} is far larger than the flow velocity, and the results were not different with the Δ*L*. For combining the velocity distributions for the 2- and 8-MHz beams, the velocity profile can be accurately obtained at a higher velocity, as shown in Figure 6.

4.3 Multi-wave method with staggered PRF trigger

The staggered PRF trigger method [3] is useful to extend the maximum measurable velocity, i.e., measure higher velocities. The pulse intervals were set at T = 0.133 ms and $T + T_s$ = 0.150 ms for measuring the velocity for the 2-MHz beam. The results are shown in Figure 7. The velocity distribution at Δ*L* = 0.74 mm is smaller than that in the LDV data. This is because of the relation between the flow velocity and the v_{allow}. The v_{allow} at Δ*L* = 0.74 mm is smaller than the maximum velocity in the channel. Therefore, it is confirmed that the measurement volume insufficient. Hence, it can be supposed that Δ*L* = 1.48 mm was required for the measurement under the given conditions. However, the velocity accuracy in the near-wall region decreases with increasing measurement volume. Thus, the multi-wave method is useful for combining velocity distributions in near-wall region with a small D_{US} and high PRF.

5 CONCLUSION

A small D_{US} with a higher f_0 is suitable for measuring velocities in the near-wall region. However, the maximum measurable velocity decreases as the basic frequency is increased. Furthermore, a low f_0 with a large D_{US} is suitable for measuring velocity distributions with increasing measurement distance. In order to overcome the limitations, the multi-wave method was proposed. The 8-MHz frequency was used for measuring the velocity in the near-wall region, and the 2-MHz frequency was used for measuring the velocity far from the transducer. By combining the two velocity profiles, the velocity profiles in the channel were accurately obtained.

REFERENCES

[1] Aritomi M et al.: Measurement system of bubbly flow using ultrasonic velocity profile monitor and video data processing unit (II), Flow characteristics of bubbly countercurrent flow,J. Nucl. Sci. Technol. 33 (1997),783-791

[2] Murakawa H et al.: Application of ultrasonic multi-wave method for two-phase bubbly and slug flows, Flow Meas. Inst. 19 (2008), 205-213

[3] Murakawa H et al.: Higher flowrate measurement using ultrasonic pulsed Doppler method with staggered trigger, In Proc. 9th ISUD (2014)