Higher Flowrate Measurement using Ultrasonic Pulsed Doppler Method with Staggered Trigger

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Ultrasonic pulsed Doppler method is a powerful tool for obtaining the velocity profile. However, the maximum detectable velocity is limited by the Nyquist sampling theorem. Furthermore, the maximum detectable velocity and the maximum measurable length are compatible. In order to overcome the limitation, staggered trigger method was applied for the method. However, the original method was low accuracy. Hence, feedback method from staggered trigger method with moving average was newly proposed. Experiments were carried out at flowrate calibration facility at AIST. It was shown that the method was useful for measuring higher velocity. Furthermore, the technique was applied for measuring flowrate, and the approximately 6 times larger flowrate was accurately obtained compared to by using the conventional pulsed Doppler method.

Keywords: Nyquist sampling theorem, maximum velocity, staggered trigger, dual PRF,

1 INTRODUCTION

Ultrasonic pulsed Doppler method has been developed mainly in medical field for blood flow measurement. The technique has several desirable characteristics, and it has been utilized for engineering field known as ultrasonic velocity profile (UVP) method [1]. The method employs multiple pulse repetition for detecting the Doppler phase shift which depends on the velocity of the reflector. Hence, the maximum detectable frequency, namely maximum detectable velocity, is limited by the Nyquist sampling theorem. The longer measurable distance is, the lower maximum velocity is. The velocity component of the ultrasonic beam direction can be obtained in the pulsed Doppler method. Therefore, it is commonly to change the transducer setting angle in order to avoid the velocity aliasing.

Dealiasing method that expands the maximum measurable velocity has been widely proposed. The spatial continuity or the time continuity were assumed for the dealiasing in the early stage. Franca and Lemmin [2] proposed a dealiasing method using four sensors. However, these techniques are limited to apply for measuring high velocity conditions that cause multiple velocity aliasing. Staggered trigger method is one of the dealiasing method that is widely used in the Doppler weather radar [3]. This technique utilizes the multiple different pulse repetition frequency (PRF) and can expand the maximum measurable velocity to the several times. The technique is also proposed for the ultrasonic Doppler method in medical field. However, it is not so commonly used for engineering field in particular for flowrate measurement.

In this paper, a new method for dealiasing based on the ultrasonic pulsed Doppler method with the staggered trigger technique is proposed. Furthermore, the applicability for the higher flowrate measurement were examined.

2 PULSED DOPPLER METHOD

2.1 Pulsed Doppler method

Schematic of the ultrasonic Doppler method is shown in Figure 1. If a pulse reflects on a moving target, the Doppler frequency, f_d, is added to the ultrasonic basic frequency, f_0. However, the f_d is much smaller than the f_0, it is difficult to obtain the f_d directly. Therefore, multiple ultrasonic pulses are required for obtaining the phase shift between consecutive echo signals [4].

The signals are considered as to be sampled by each pulses with f_{prf} (=1/T). Hence, the maximum detectable velocity, v_{max}, is limited by the Nyquist sampling theorem as

$$v_{max} = \frac{c}{4 f_0 T} . \tag{1}$$

On the other hand, the maximum measurable length, $L_{\max}$, is determined by the time-of-flight of the pulse to travel back and forth from a transducer as

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

Hence, it is impossible to increase the both v_{max} and L_{max} at the same time.

2.2 Staggered trigger method

A staggered trigger method is that pulses are emitted at different interval, and the phase shift is

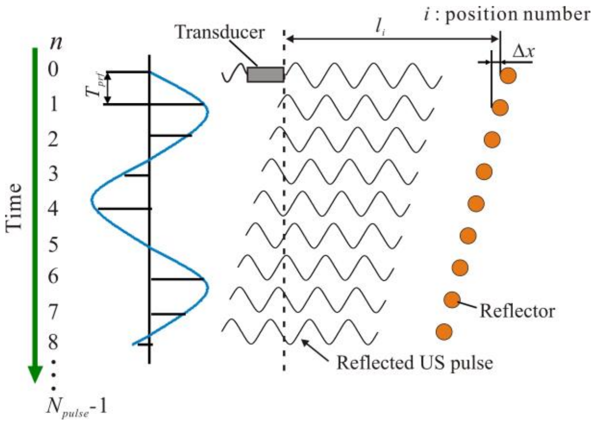


Figure 1: Schematic of the pulsed Doppler method

calculated between the pulses. As an example, dual PRF case is shown in Figure 2. Pulses are emitted at intervals of T and $T + T_s$, and the phase change between each trigger interval, $\Delta\theta_1$, $\Delta\theta_2$ can be obtained as;

$$\Delta\theta_1 = 2\pi f_d T \tag{3}$$

$$\Delta\theta_2 = 2\pi f_d (T + T_s) \tag{4}$$

Hence, the difference between the phase shifts is expressed as

$$\Delta\Delta\theta = \Delta\theta_2 - \Delta\theta_1 = 2\pi f_d T_s . \tag{5}$$

The velocity is calculated from

$$v = \frac{c \cdot \Delta\Delta\theta}{4\pi f_0 T_s} . \tag{6}$$

The $\Delta\Delta\theta$ is ranged from $-\pi$ to π. Therefore, the maximum detectable velocity is

$$v_{max} = \frac{c}{4 f_0 T_s} . \tag{7}$$

Comparing the Eq.(6) with Eq.(1), it is known that v_{max} can increase with T/T_s times.

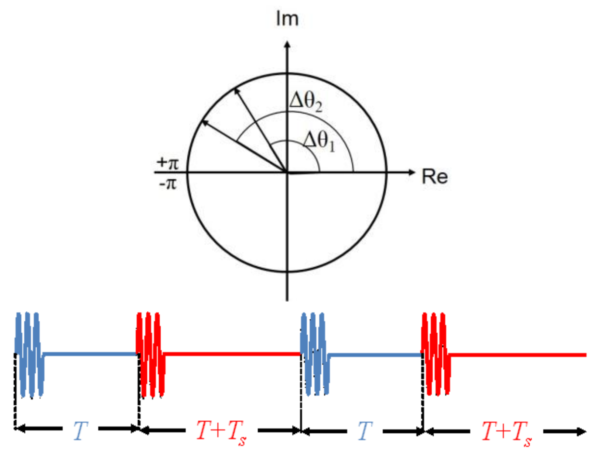


Figure 2: Schematic of the staggered trigger method

3 EXPERIMENTAL FACILITIES

The UVP system is Lab. made. It composes of an ultrasonic pulser/receiver (JPR-2CH-KB, Japan Probe, Co., Ltd.), a high-speed digitizer (PXI-5114, National Instruments Corp.), a programmable function generator and a PC. The measurement software was developed by using C++ and LabView. Ultrasonic is emitted by an ultrasonic transducer at 2MHz with 10 mm sensor diameter. The pulser/receiver is connected with the function generator to control the pulse emission interval.

Applicability of the staggered trigger method to the flowrate measurement is examined at a flowrate calibration facility at NMIJ, AIST in Japan. The test section is a horizontal pipe with 200 mm in diameter, *D*. The working fluid was water, and micro bubbles were injected in the flow for reflector of the ultrasonic. A rectifier was set at the downstream of the bubble injection. The ultrasonic transducer was set at contact angle of 20º as shown in Figure 3. The measurement position was downstream of 55*D* from the rectifier. The flowrate was measured at weighing system located downstream of the test section. The stagnation of the micro bubbles could be neglected at the front face of the transducer.

The flowrate, Q, was ranged from 80 to 500m^3/h that is Re = 1.4 ~ 8.5 × 10^5. The number of pulse repetition for obtaining an instantaneous velocity profile, N_{pulse}, and the number of pulse cycle, N_{cycle}, which correspond to the spatial resolution along the ultrasonic beam were changed. The maximum measurable flowrate with normal pulsed Doppler method is about 90 m^3/h in these settings. In the measurement, echo signals were recorded continuously, the velocity calculations were conducted after the measurements for comparing the calculation algorithms.

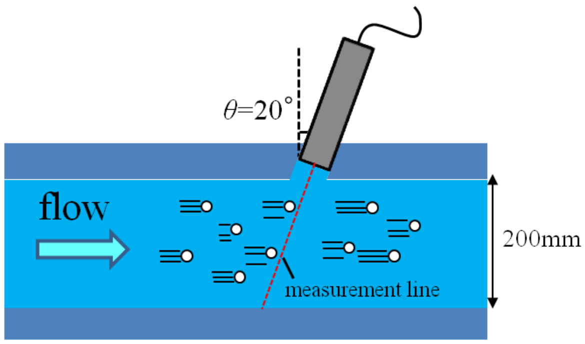


Figure 3: Test section and the transducer setting

4 RESULTS AND DISCUSSIONS

4.1 Instantaneous velocity profile with staggered trigger method

An instantaneous velocity profile obtained by using the staggered trigger method is shown in Figure 4. The experimental conditions were Q =

500 m^3/h, N_{pulse} = 512 and N_{cycle} = 8, T = 0.5 ms, T_s = 0.08 ms. The vertical axis indicates the instantaneous velocity converted to the mainstream direction. The continuous line indicates velocity distribution obtained from the power low calculated from the flowrate. The maximum velocity in the conventional Doppler method expressed in Eq.(1) is 0.127 m/s. Although the higher velocity than the maximum velocity in the conventional method could be obtained, it includes much measurement error. This is because it calculates the difference of the phase change between the $\Delta\theta_1$ and $\Delta\theta_2$. As a result, the staggered trigger method tend to be affected by noises rather than the conventional method. Furthermore, the uncertainties of the T and T_s also affects the velocity error. Therefore, it is known that the staggered trigger method cannot be used directly for the UVP measurement.

In order to improve the staggered trigger method, feedback method is applied. Velocity data obtained by the staggered trigger include much error. Therefore, the data is used for velocity index for deciding the number of aliasing. If velocity, v, obtained by using the conventional method may occurs the velocity aliasing for several times, the real velocity, v_{real}, is expressed as

$$v_{real} = v + 2mv_{\max} \quad (8)$$

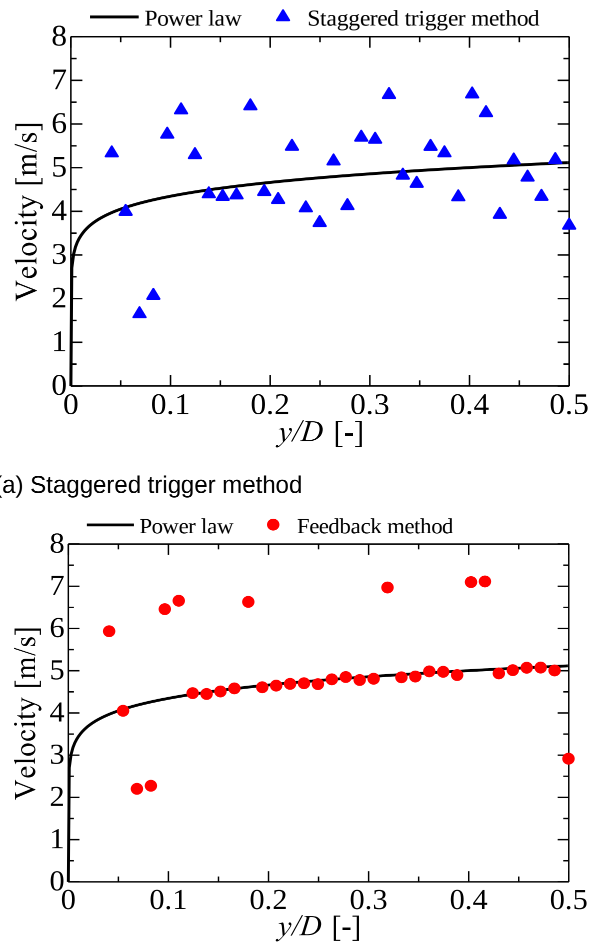
Where, m is the number of aliasing. If the m can be estimated, the v_{real} is obtained. In order to decide the m, staggered trigger method is used for limiting the velocity range to satisfy the following equation.

$$v_{stg} - v_{\max} < v_{real} \leq v_{stg} + v_{\max} \quad (9)$$

Where, v_{stg} is the velocity obtained from the staggered trigger method, and v_{max} is the maximum velocity based on the T. In the measurements, the echo signals were continuously recorded at the intervals of T and T+T_s by turn. In order to calculate the v in the Eq.(8), average phase shifts at the interval of T, $\overline{\Delta\theta_1}$ and T+T_s, $\overline{\Delta\theta_2}$, were calculated, and the average phase shift obtained with the conventional method is

$$\overline{\Delta\theta} = \left(\overline{\Delta\theta_1} + \overline{\Delta\theta_2}\right)/2 \quad (10)$$

Result of the feedback method is shown in Figure 4(b). The original echo signals used for the velocity calculation are completely the same with the Figure 4(a). It is confirmed that the accuracy of the instantaneous velocity is improved. However, the much higher or lower velocities are confirmed at some measurement position. The velocity differences between the power law and the obtained velocity are approximately ±2v_{max}. It



(a) Staggered trigger method

(b) Feedback method

Figure 4: Instantaneous velocity distributions (Q = 500 m^3/h, N_{pulse} = 512)

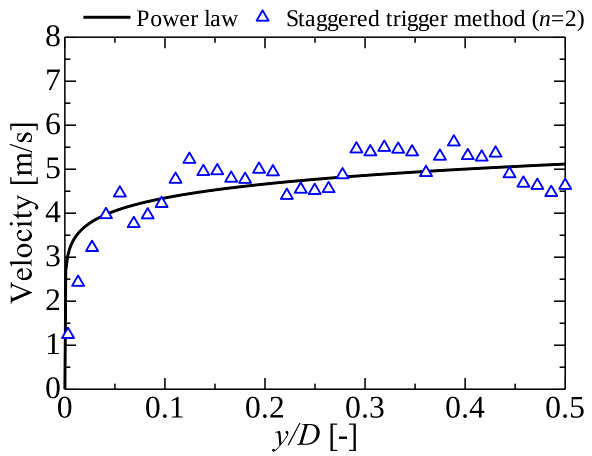
means the number of aliasing, m, were false detection at the some measurement positions. It is because the v_{std} had velocity error larger than ±v_{max} from the real velocities.

4.2 Feedback method using moving average of the v_{stg}

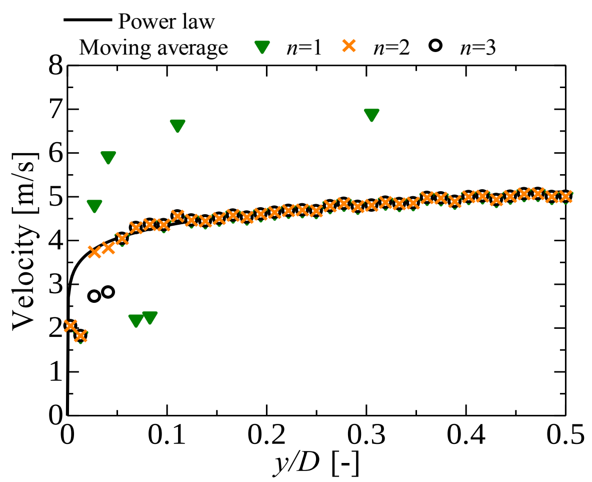
As shown in Figure 4, the feedback method also include some velocity errors, which comes from the large uncertainty of the velocity index of the v_{std}. In order to improve the index accuracy, moving average defined in Eq.(11) was applied to the v_{std}.

$$v_{stg} = \frac{v_{1,i-n} + v_{1,i-(n-1)} + \cdots + v_{1,i} + v_{1,i+(n-1)} + v_{1,i+n}}{(2n+1)} \quad (11)$$

Figure 5(a) represents the results of the v_{std} with moving average of n = 2. Although the velocity distribution is much different with the power law, the velocity fluctuation is much flatten compared to the Figure 4(a). The velocities in each measurement position were used for the velocity index, and the feedback method was applied as shown in Figure 5(b). Here, it should be noted that the moving average reduces the spatial resolution. However, the v_{stg} is only used for the velocity index. Therefore, it does not reduce the spatial resolution of the obtained velocity distributions. Although, the velocity error also confirmed near wall region, the instantaneous velocity distributions were much better than the Figure 4(b). Therefore, it is confirmed that the proposed method is useful for calculating the instantaneous velocity distributions at higher velocity.



(a) Staggered trigger method with moving average (n=2) , this profile was used as velocity index for deciding the number of aliasing in each position



(b) Feedback method

Figure 5: Feedback method with moving average of the v_{stg}

4.3 Flowrate measurement

The proposed method was applied for the flowrate measurement. Instantaneous velocity profiles were used for calculating the flowrate [5], and 1,000 data were averaged. The results are shown in Figure 6. The vertical axis indicates the flowrate measured by the UVP using the proposed algorithms of the feedback method with moving average. The horizontal axis indicates the flowrate measured by the weighing system, which can be considered as the true value. The maximum measurable flowrate in the conventional UVP system is approximately 90m^3/h. With increases of the flowrate, N_{cycle} must be set at larger value. The flowrate error was -0.8% with N_{cycle} = 8 at 500 m^3/h. Therefore, the proposed new algorithms could be used for measuring approximately 6 times larger flowrate compared to by using the conventional UVP method.

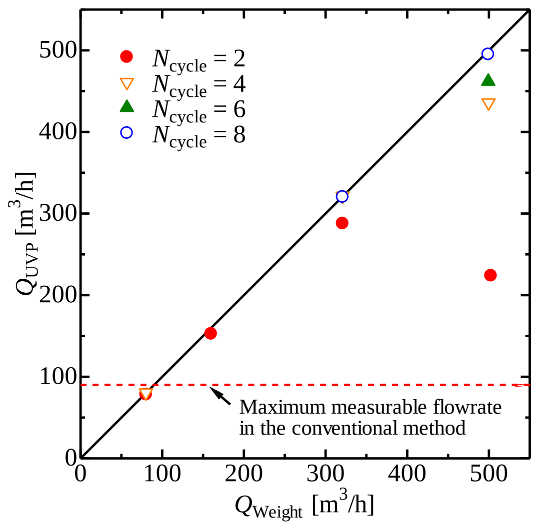


Figure 6: Flowrate measurement

5 SUMMARY

Ultrasonic pulsed Doppler method has maximum detectable velocity defined by the Nyquist sampling theorem. In order to exted the velocity limitation, feedback method using staggered trigger method with moving average was proposed. The technique could measure much higher velocity than the conventional method. Furthermore, it was applied to the flowrate measurement, and it was shown that approximately 6 times larger flowrate could be accurately obtained.

REFERENCES

[1] Takeda Y: Development of ultrasound velocity profile monitor, Nuclear Engineering and Design 126 (1990), 277-284.
[2] Franca MJ, Lemmin U: Eliminating velocity aliasing in acoustic Doppler velocity profiler data, Meas. Sci. Tech. 17 (2006), 313-322.
[3] Holleman I, Beekhuis H: Analysis and Correction of Dual PRF Velocity Data, J. Atmos. Ocean. Technol. 20 (2003), 443-453.
[4] Takeda Y (ed): Ultrasonic Doppler velocity profiler for fluid flow, Springer Japan (2012), Chap.3
[5] Mori M, Takeda Y, Taishi T, Furuichi N, Aritomi M., Kikura H: Development of a novel flow metering system using ultrasonic velocity profile measurement, Exp. Fluids 32 (2002), 153-160.