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Velocity Profile Measurement Using Ultrasonic Pulse-Train Doppler Method Under the Disturbed Flow Condition

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This paper presents experimental measurements using the novel technique for measuring the velocity profile and flow rate in a pipe. This method, named the ultrasonic pulse-train Doppler method (UPTD), has the advantages of expanding the velocity range and setting the smaller measurement volume with low calculation and instrument costs in comparison with the conventional ultrasonic pulse Doppler method. In addition, previous reports indicate that a smaller measurement volume increases the accuracy of the measurement. In consideration of the application of the conventional method to actual flow fields, such as industrial facilities and power plants, the issues of velocity range and measurement volume are important. Experimental measurements were conducted, and the results were evaluated at the national standard calibration facility of water flow rate in Japan. The results show that UPTD can measure the velocity profiles over the pipe diameter, even if the velocities exceed the measurable velocity range under the straight pipe condition. In addition, to examine the applicability of UPTD to the flow condition with large velocity fluctuation, velocity profiles were measured using UPTD under the disturbed flow condition and compared with the conventional Doppler method.

Keywords: Flowrate, Velocity profile, Ultrasound, Doppler, Pulse-train

1. Introduction

It is well known that the measured flow rate given by flowmeters, such as ultrasonic, electromagnetic, and turbine flowmeters, generally depends on the velocity profile in a pipe. This dependence demonstrates that the measurement accuracy of these flowmeters is influenced by the upstream pipe configuration, even if the flowmeters are calibrated by a calibration facility. In calibration facilities, the construction of a complete equivalent pipe layout in an actual field is often difficult, and thus on-site calibration is the only practical method of checking the accuracy of the flow rate measurement. Although an on-site flowrate calibration method with high accuracy is expected for actual field measurements, few existing methods achieve high accuracy. For example, Guntermann et al. [1] proposed an on-site calibration method using a laser Doppler velocimetry (LDV) system. In this method, the reference flowrate in the actual flow field was estimated by using the velocity profile measured by the LDV system. However, modifications of the pipe were necessary before using the LDV system.

The ultrasonic pulse Doppler method was developed to measure blood flow [2]. Due to its outstanding advantages, such as non-invasiveness and spatiotemporal measurement, this method has been applied in the engineering field by Takeda [3] and widely used to investigate flow dynamics [4]. Mori et al. developed a flowmeter for pipe flow by employing this method [5]. This type of flowmetering method can possibly be applied to on-site calibration as a clamp-on measurement [6]. In other words, this method is expected to avoid modifications of the existing pipe. Because the basic principle of flow rate measurement consists of measuring the velocity profile over a pipe diameter and integrating the measured profile, this method can also reduce the influence of a disturbed flow caused by upstream pipe conditions. Furuichi performed a fundamental uncertainty analysis of this flowmetering method under ideal flow condition, i.e., an asymmetric velocity profile [7].

On the other hand, the ultrasonic pulse Doppler method, which is based on the Nyquist sampling theorem, has a limited velocity measurement range. In consideration of the application of this method to actual flow fields, such as industrial facilities and power plants, one major issue is its limitation for large pipes and flow rates. Developments, such as the staggered frequency of the pulse repetition method [8][9] and the multiple demodulation frequency method to overcome the Nyquist limitation, have been widely studied [10][11]. In recent years, Tanaka et al. [12] investigated the wideband Doppler method. These studies were conducted for blood measurements and weather radar measurements. However, the literature concerning the accuracy of velocity and flowrate measurements in a pipe flow is limited. An application of the staggered frequency of pulse repetition on a pipe flowrate measurement was presented by Murakawa et al. [13]. The report indicates that the accuracy of the velocity profile obtained by the conventional staggered frequency method is low for industrial applications. Although they also reported the result of flow rate measurements with high accuracy by using the multi-wave method [14], applying the multi-wave method as a clamp-on measurement will be difficult due to the multiple scattering of ultrasound in a pipe wall. In addition, they noted that a smaller measurement volume increases the accuracy of the measurement.

We presented a novel technique of measuring a velocity profile, named the ultrasonic pulse-train Doppler method (UPTD) [15]. This method has the advantages of expanding the velocity range and setting the smaller measurement volume with low calculation and instrument costs in comparison with the conventional ultrasonic pulse

Doppler method. The algorithm is to exploit a few pulses of ultrasound with a short interval and an envelope detection. In this paper, to examine the applicability of UPTD to the flow condition with large velocity fluctuation, velocity profiles were measured using UPTD under the disturbed flow condition and compared with the conventional Doppler method.

2. UPTD

2.1 Principle of measurement

A schematic representation of the signal processing of UPTD is given in Figure 1. First, two pulses are transmitted with a delay of T_{pt} from the transducer and repeated with an interval of T_{prf}. Then, a set of two pulses with delay T_{pt} is reflected on a particle and detected by the same transducer. The detected pulse is amplified and processed by envelope detection, which consists of the calculation of the absolute value and low-pass filtering. The cutoff frequency of the low-pass filter is determined by considering the frequency of the ultrasound and the delay of the pulse train. The T_{pt} is better to be set over the duration of a single pulse for the envelope detection. Consequently, the path, diverging angle and straightness of the pulsed ultrasound of UPTD is almost same with the case of using a single pulse.

A block diagram of signal processing for the UPTD method is shown in Figure 2. The output signal through the envelope detection has frequency f_{pt}, which is defined by the delay time of pulse train T_{pt}. The Doppler frequency can be obtained by quadrature detection using a reference wave with frequency f_{pt}. As a result, the velocity range depends on frequency f_{pt}. In other words, the maximum measurable velocity is denoted in the following equation.

$$v_{\max\_\mathrm{UPTD}} = \frac{c}{4 f_{pt} T_{prf} \sin\alpha} \tag{1}$$

From this equation, we can observe that UPTD can determine the velocity range flexibly, because f_{pt} is independent of the center frequency of the ultrasound. This flexibility also means that UPTD can employ a smaller measurement volume by using the higher central frequency of the ultrasound.

Table 1 shows the velocity ranges of the conventional method for f_0 = 1 MHz and 4 MHz in the direction of the pipe axis. In this experiment, the velocity range using UPTD is expected to extend as high as the range using the conventional method with f_0 = 1 MHz, because the delay of the pulse train is set at 1 μs.

Table 1 Velocity range of the conventional ultrasonic pulse Doppler method

Center frequency: f_0	Velocity range: v_{range}
1 MHz	5.7 m/s
4 MHz	1.4 m/s

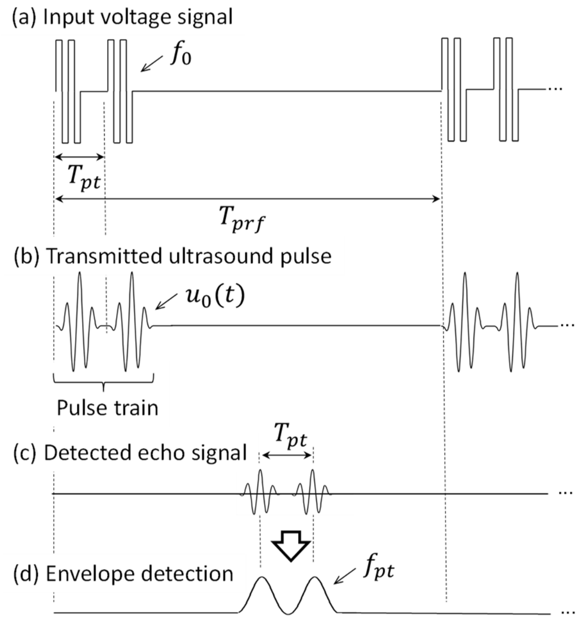

Figure 1: Schematic of signal processing of ultrasonic pulse-train Doppler method.

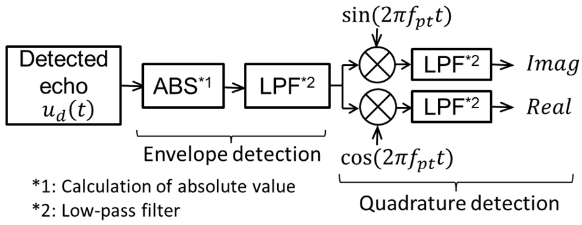

Figure 2: Block diagram of ultrasonic pulse-train Doppler method.

3. Experiment

3.1 Experimental apparatus and conditions

Experiments were performed at the water flow rate calibration facility of the National Institute of Advanced Industrial Science and Technology, National Metrology Institute of Japan (AIST, NMIJ). This facility is the national standard calibration facility of water flow in Japan. The flow rate given by the UPTD method was evaluated with respect to the reference flow rate given by the electromagnetic flowmeter calibrated by the static gravimetric method using a tank system weighing 50 t. The uncertainty of the reference flow rate given by the 50 t weighing tank system was 0.060% (k = 2). For details of the system, see reference [16]. The flow rate range of this experiment was 200 m^3/h, and the water temperature condition was 27.3 ± 1.0 °C. The temperature variation was within 0.1°C during one measurement. The Reynolds number was $Re = 4.12 \times 10^5$. Figure 3 shows the schematic of the test facility and the test section. The pipe layout with the bubble generator was the same as that used in the previous study by Furuichi [7]. The flow conditioner was installed at a distance of 55D upstream of the test section. Small air bubbles that act as reflectors of ultrasound were inserted upstream of the flow conditioner. The bubble sizes were confirmed using a high-speed camera to be much smaller than 1mm [17]. The ultrasonic transducer was installed in the test pipe and placed in direct contact with the water. The incident angle of the transducer was α = 19.3°, which was obtained from actual measurement. The inner diameter of the test pipe was D = 199 mm.

To generate a disturbed (non-axisymmetric) flow, obstacle plate as shown in Figure 4 is installed upstream of the test section. This type of plate is frequently used in performance tests of flowmeters [18]. The aperture ratio of these obstacle plates in this paper is 0.66. The installation direction of the obstacle plates is shown in Figure 4. The expected velocity profile downstream of the single plate is similar to one of an elbow. The inlet length, the distance between the plate and the test section, is 8D.

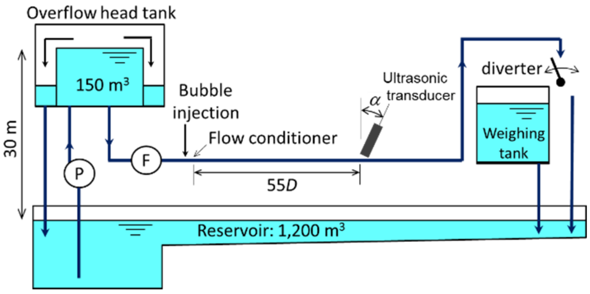

Figure 3: Experimental facility and test section.

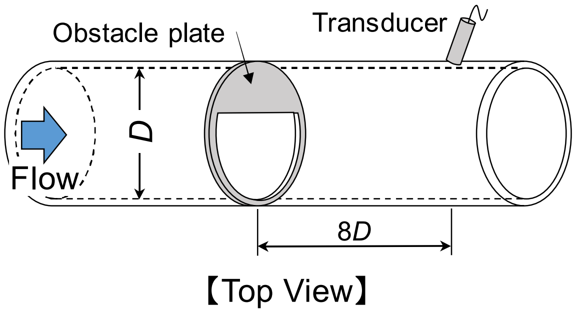

Figure 4: Layout of the obstacle plate.

An input voltage signal with two cycles per pulse generated by using the pulser-receiver instrument (JPR-10CN, Japan Probe Co., LTD.) was applied to the ultrasonic transducer, and pulsed ultrasound was transmitted into water. The reflected pulses of ultrasound were detected by the same transducer and amplified by the same pulser-receiver. These amplified signals were transferred to the digitizing instrument (NI-5122, National Instruments Co.). The pulse train was also generated and transmitted by the same pulser-receiver. Table 2 shows the experimental conditions in this experiment. All the measurements were made with the same receiving gain and power amplification settings.

Table 2 Experimental conditions

Center frequency of ultrasound: f_0	4 MHz
Incident angle of ultrasound: α	19.3°
Length between transducer and internal pipe wall: L_s	39 mm
Length of measurement volume along ultrasonic beam: L_{cw}	1.5 mm
Diameter of piezo element: d_{us}	5 mm
Diameter of pipe: D	199 mm
Sound speed of water: c	1504 m/s
The time interval of pulse repetition: T_{prf}	400 µs
The delay time of the pulse-train: T_{pt}	1 µs

3.2 Results

The time-averaged velocity profile under the straight pipe condition is shown in Figure 5. The horizontal axis means that r/D = –0.5 is the inner pipe wall near the transducer, r/D = 0 is the center of the pipe and r/D = 0.5 is the opposite inner pipe wall of the transducer. The distance between measurement points along the ultrasonic path is 2.3 mm. This figure indicates that UPTD can measure velocity profiles over the pipe diameter, even if these velocities exceed the measurable velocity range of the conventional pulse Doppler method.

Figure 6 shows the time-averaged velocity profiles under the disturbed flow condition. The conventional method using the 4MHz transducer cannot measure the velocity profile due to the velocity range and the large velocity fluctuation. On the other hand, UPTD with 4MHz and the conventional method with 1MHz can measure velocity profile because the wide velocity range. However, the velocities near the pipe wall measured by the conventional method with 1MHz are estimated to be influenced by the larger measuring volume and the reflected ultrasound on the pipe wall.

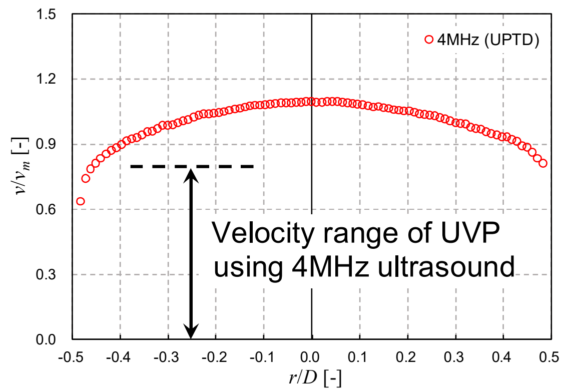

Figure 5: Time-averaged velocity profile measured by UPTD using 4MHz ultrasound under the straight pipe condition.

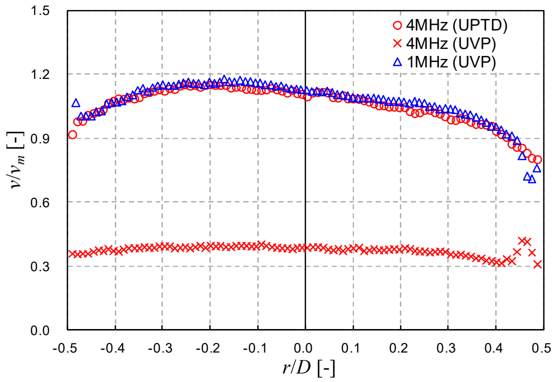

Figure 6: Time-averaged velocity profiles measured by UPTD (4MHz) and UVP (4MHz and 1MHz) with the obstacle plate condition.

4. Conclusions

This paper presents the ultrasonic pulse-train Doppler method (UPTD), a novel technique of measuring the velocity profile and flow rate in a pipe. UPTD has the advantages of expansion of the velocity range and a capability to decrease in measurement volume with low calculation and instrument costs in comparison with the conventional method. The UPTD algorithm exploits two pulses of ultrasound with a short interval and envelope detection. Experimental measurements were performed at the national standard calibration facility of water flow rate in Japan. The result shows that UPTD can measure the velocity profiles over the pipe diameter, even if these velocities exceed the measurable velocity range of the conventional pulse Doppler method. In addition, to examine the applicability of UPTD to the flow condition with large velocity fluctuation, velocity profiles were measured using UPTD under the disturbed flow condition and compared with the conventional Doppler method. These results show that UPTD can measure velocity profile under the disturbed flow condition.

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