Application of Partial Inversion Pulse on velocity profile and flowrate measurement using Ultrasonic Time-Domain Correlation method

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This paper presents an application of a novel ultrasonic pulse, Partial Inversion Pulse (PIP), to the velocity profile and flowrate measurement using Ultrasonic Time-Domain Correlation (UTDC) method. In general, a measured flowrate depends on the velocity profile in a pipe, thus an on-site calibration is the only method of checking the accuracy of flowrate measurements in the fields. UTDC is a type of flow metering method that is applicable to the on-site calibration. The principle of the flowrate calculation is based on the integration of the measured velocity profile. The advantages of this method compared with the ultrasonic pulse Doppler method are the possibility of no-limitation of velocity range and applicability to flow fields without enough reflectors. Previous studies reported, however, that UTDC has also a limitation of velocity range because of the false detection. To overcome the false detection, we have developed a new waveform of pulsed ultrasound. Experimental measurements were performed at the national standard calibration facility of water flowrate in Japan. The results indicate that UTDC employing PIP can measure velocity profiles and flowrates with higher accuracy than the conventional method.

Keywords: Flowrate, Velocity profile, ultrasound, Time-domain correlation, Partial inversion pulse

1. Introduction

It is well known that the measured flowrate given by flowmeters, such as ultrasonic, electromagnetic, and turbine flow meters, generally depends on the velocity profile in a pipe. This demonstrates that the measurement accuracy of these flowmeters is influenced by the upstream pipe configuration even if flowmeters are calibrated by a calibration facility. In calibration facilities, the construction of a complete equivalent pipe layout with an actual field is often difficult, and thus an on-site calibration is the only method of checking the accuracy of flowrate measurement. An on-site calibration is a comparison test using a reference flowmeter in the fields. Although the establishment of an on-site calibration method with high accuracy is expected for actual fields, there are a few methods that realize it. For instance, 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 is estimated using the velocity profile measured by the LDV system. However, modifications to the pipe are necessary to use the LDV system.

Mori et al. [2] have developed the flowmeter based on the ultrasonic pulse Doppler method (UDM). This type of flow metering method has a possibility of being applied to an on-site calibration. Since the basic principle of the flowrate measurement consists of measuring a velocity profile over a pipe diameter and integrating the measured profile, this method is expected to remove the necessity of modifying the existing pipe. Furuichi performed a fundamental uncertainty analysis of this flow metering method under the ideal flow condition [3] and Wada et al. reported the experimental results under disturbed flow conditions [4].

On the other hand, ultrasonic time-domain correlation method (UTDC) has been developed in the medical field to exceed the velocity range of UDM [5][6][7]. Owing to its outstanding advantage of the high time resolution, UTDC has been applied in the engineering field [8][9]. In principal, UTDC has advantages which are a possibility of no-limitation of velocity range and an applicability to a flow condition without enough reflectors. Considering the application to actual flow fields, such as industrial facilities and power plants, these advantages are important to measure the large flowrate and to reduce the impact of reflectors on the facilities. The literature concerning the evaluation of velocity range is, however, limited. Some studies have suggested that UTDC has also a limitation of velocity range and needs an adequate threshold of cross-correlation coefficient to avoid the false detection of the sidelobe [10][11].

In this paper, we present an application of a novel pulsed ultrasound, Partial Inversion Pulse (PIP), to a velocity profile and flowrate measurement using UTDC. This method is based on the pulse compression technique [12] and has an advantage to expand the velocity range with high accuracy in comparison to the conventional UTDC. PIP can reduce the sidelobe of cross-correlation coefficient by inversing a pulsed ultrasound partially. Experimental measurements were performed and the results were evaluated at the national standard calibration facility of water flowrate in Japan.

2. UTDC

2.1 Principle of measurement

A schematic of flow velocity measurement using UTDC is illustrated in Figure 1. In general, a cross-correlation coefficient is determined by following equation,

$$R_k = \frac{\sum_{t=1}^{n} u_0(t) \cdot u_1(t)}{\sqrt{\sum_{t=1}^{n} u_0^2(t)}\sqrt{\sum_{t=1}^{n} u_1^2(t)}} \tag{1}$$

where, u_0 and u_1 are the detected waveforms in the reference and search windows.

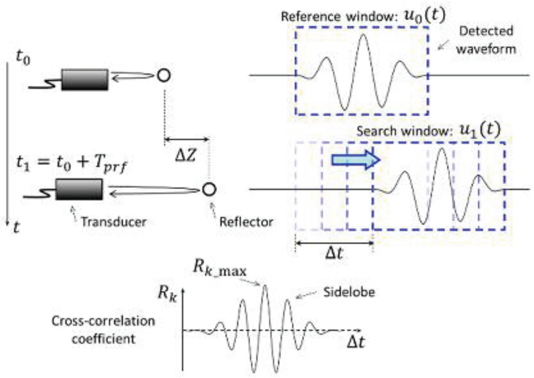


Figure 1: Schematic of flow velocity measurement using UTDC.

2.2 Partial Inversion Pulse

An input voltage signals of the normal pulse and PIP are presented in Figure 2. In normal case, a pulse with two cycles of T_0 are transmitted from a transducer and repeated with an interval of T_{prf}. Then the pulsed ultrasound is reflected on a particle and detected by the same transducer. On the other hand, PIP has a delay time of $0.5T_0$ between the two cycles. In this manuscript, we report only the case of two cycles per pulse and the delay time of $0.5T_0$. It needs to study an influence of the number of cycles and the delay time on the flow measurement in the future work.

Figure 3 shows the actual waveforms of pulsed ultrasound with the frequency of 2MHz. This figure indicates that PIP can be formed successfully. The cross-correlation coefficients of the normal pulse and PIP are illustrated in Figure 4. The coefficient of the sidelobe is approximately R_k = 0.7 in the normal pulse case. On the other hand, the sidelobe of PIP is reduced to approximately R_k = 0.4 due to the result of the inversion region.

3. Experiment

3.1 Experimental apparatus and conditions

The experiments were performed at the water flowrate 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 flowrate given by UTDC with PIP was evaluated with respect to the reference flowrate given by the electromagnetic flowmeter calibrated by the static gravimetric method using a tank system weighing 50 t. The uncertainty of the reference flowrate given by the 50t weighing tank system is 0.060% (k = 2). For the details of the system, see reference [13]. The flowrate of this experiment was 400m^3/h, and the water temperature condition was 17.3±1.0 °C. The temperature variation was within 0.1 °C during one measurement. The Reynolds number was $Re = 6.61 \times 10^5$. Figure 5 shows the schematic of the test facility and the test section. The pipe layout with the bubble generator was the same as in the previous study [3]. The flow conditioner was installed a distance of 55D upstream of the test section. Small bubbles that act as reflectors of ultrasound were inserted upstream of the flow conditioner [14]. The ultrasonic transducer was installed in the test pipe and placed in direct contact with the water. The incident angle of transducer was α = 19.7° which was obtained from an actual measurement. The inner diameter of the test pipe was D = 199 mm.

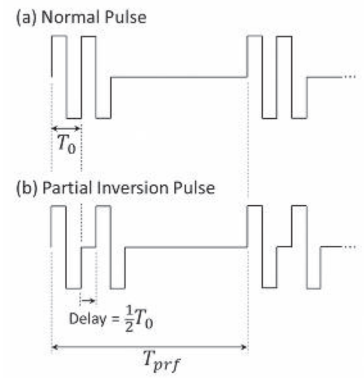


Figure 2: Input voltage signals of the normal and partial inversion pulses.

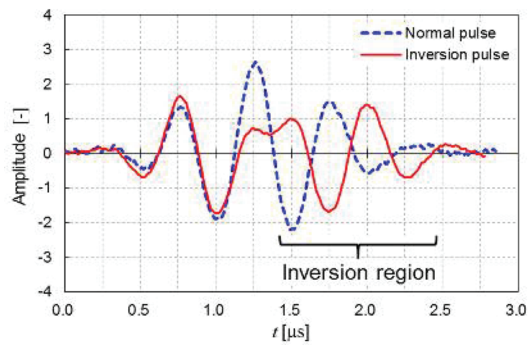


Figure 3: Waveforms of pulsed ultrasound in case of normal pulse and PIP.

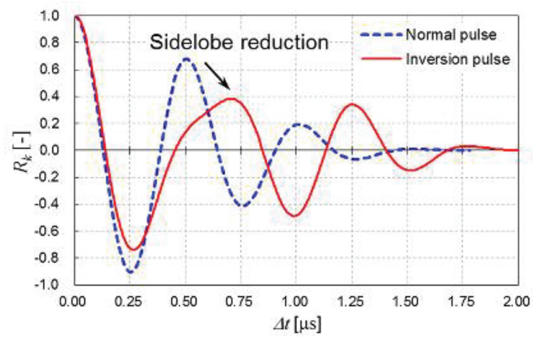


Figure 4: Cross-correlation coefficients in case of normal pulse and PIP.

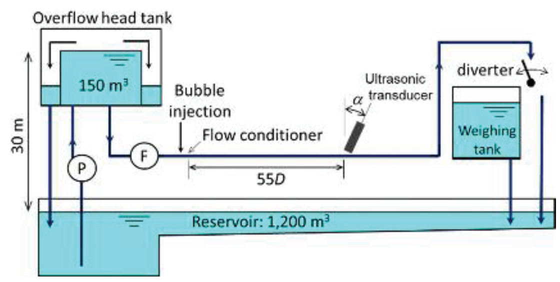


Figure 5: Experimental facility and test section.

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 a pulsed ultrasound was transmitted into water. Reflected pulses of ultrasound were detected by the same transducer and amplified by using the same pulser-receiver. These amplified signals were transferred to the digitizing instrument (NI-5122, National Instruments Co.). PIP was also generated and transmitted by the same pulser-receiver. The time interval of pulse repetition was set at 400 μs and the delay time of PIP was set at 0.25 μs. The central frequency of the ultrasonic transducer was f_0 = 2 MHz, and the diameter of the piezoelectric element was 10 mm. All the measurements we present were made with the same receiving gain and power amplification settings. The distance between measurement points along the ultrasonic path was 2.2 mm.

The sampling rate of the digitizing instrument was 100MHz. The width of reference and search windows were set at 3 μs to cover the entire range of the pulsed ultrasound as shown in the previous chapter. The determination of the threshold of cross-correlation coefficient is important to eliminate the false detection especially under small signal to noise ratio. The threshold was changed from 0.5 to 0.9 in this experiment.

The measurable velocity of UDM can be calculated according to the following equation,

$$v_{\max} = \frac{c}{4 f_0 T_{prf} \sin\alpha} \qquad (2)$$

where, c is the sound speed of water, f_0 is the center frequency of ultrasound, T_{prf} is the time interval of pulse repetition and α is the incident angle of ultrasound. Since this method can measure the both velocity directions, going away from and approaching the transducer, the velocity range is given by the equation.

$$v_{\text{range}} = 2 v_{\max} \qquad (3)$$

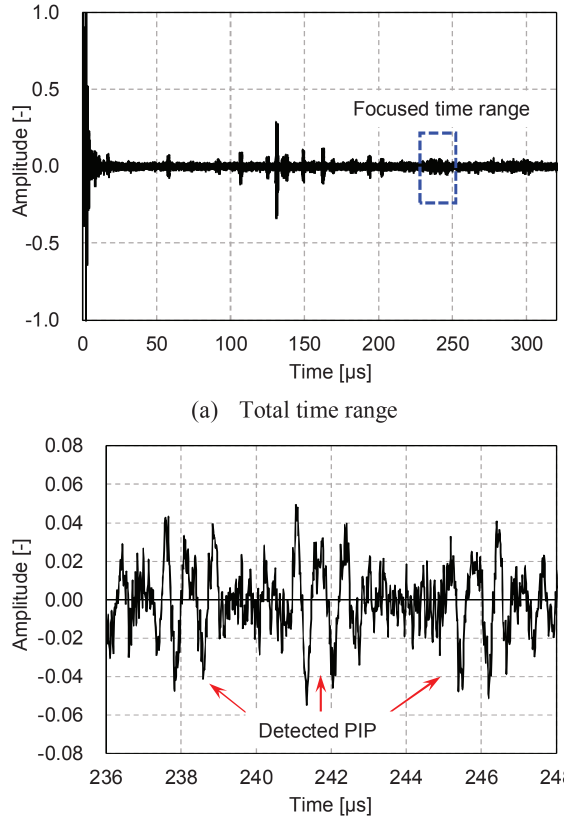
In this paper, the velocity range of UDM for f_0 = 2 MHz in direction of the pipe axis is approximately 2.8 m/s. Consequently, the experimental flowrate was set at 400 m^3/h to exceed the measurable velocity of UDM.

3.2 Results

An example of detected signal over the pipe region is shown in Figure 6(a). The delay time calculated by using the distance between the transducer and the inner pipe wall of the opposite side is approximately 300 μs, thus this figure demonstrates that the transducer can detect the pulses reflected on particles all over the pipe region. To confirm the shape of PIP signal, the enlarged figure is provided in Figure 6(b). PIP can be observed clearly and every detected signals have the inversion region as illustrated in this figure.

The time averaged velocity profiles at the threshold of R_{Th} = 0.7 are illustrated in Figure 7. The horizontal axis is the position over the pipe and the vertical axis is the normalized velocity. It is important to consider the number of particles passing through a measurement volume during one measurement. Under the same number density of particles, the number of pulse repetition for calculating one averaged profile is better to be determined depending on the flowrate. In this paper, the number of pulse repetition is set at N_p = 38,400 for Q = 400 m^3/h. The time of one measurement is approximately 15 s. This figure indicates that the all velocities obtained using the normal pulse are smaller than the velocities using PIP. This is expected that the influence of the false detection on the velocities using the normal pulse is larger than that using PIP.

In general, the flowrate is calculated by integrating the velocity profile which is obtained in the region from r/D = 0 to r/D = 0.5 [15]. This is because that it is necessary to avoid the effect of the large stable signals occurred in the transducer or in the pipe wall near transducer. Figure 8



(a) Total time range

(b) Focused time range of (a)

Figure 6: Snap shot of detected signal.

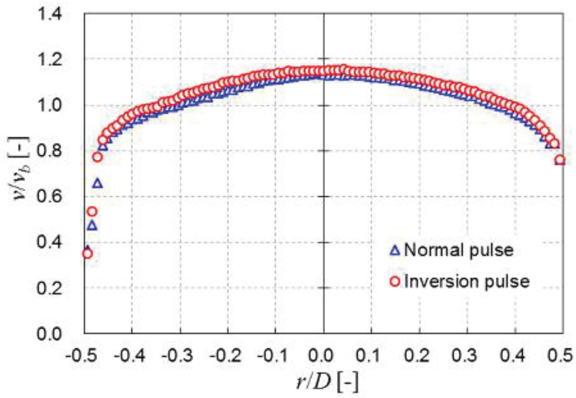


Figure 7: Mean velocity profiles at R_{Th} = 0.7.

shows the difference of measured flowrate between by using UTDC and by using the reference flowmeter. The difference is expressed as the equation,

$$E_Q = \frac{Q_{\mathrm{UTDC}} - Q_{\mathrm{ref}}}{\mathrm{Q}_{\mathrm{ref}}} \qquad (4)$$

where, Q_{UTDC} and Q_{ref} are the flowrates measured by using UTDC and the reference flowmeter, respectively. As a result, UTDC with PIP can measure the flowrate with high accuracy under ±0.3 % when the threshold of cross-correlation coefficient is equal to or higher than 0.7. In conclusion, UTDC with PIP allows an expansion of velocity range with a superior accuracy. It remains challenges for future research to evaluate effects of increasing number density of particles and disturbing flow condition such as downstream of an elbow or a valve.

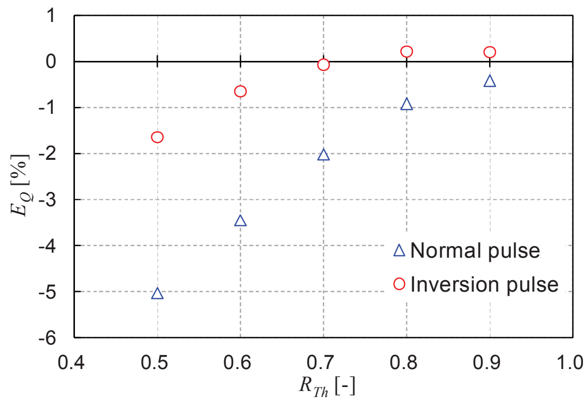


Figure 8: The differences of measured flowrate between by using UTDC and by using the reference flowmeter.

4. Conclusions

This paper presents an application of a novel ultrasonic pulse, Partial Inversion Pulse, to the velocity profile and flowrate measurement using UTDC. This method has an advantage to expansion the velocity range with high accuracy in comparison with the conventional one. PIP can reduce the sidelobe of cross-correlation coefficient by inversing a pulsed ultrasound partially. Experimental measurements were performed and the results were evaluated at the national standard calibration facility of water flowrate in Japan.

The results of the experiments show that all detected signals have a partial inversion region in a pulse. UTDC with PIP can measure the velocity profiles over the pipe diameter even if these velocities exceed the measurable velocity range of UDM. In addition, the accuracy of flowrates calculated by using the measured velocity profiles are under ±0.3 % when the threshold of cross-correlation coefficient is equal to or higher than 0.7.

It is found that the validity of UTDC with PIP has been shown by the development of an ultrasound generator that can form PIP. It remains some challenges for future research to evaluate an influence of the increasing number density of particle, and disturbing flow condition such as downstream of an elbow or a valve.

Acknowledgment

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References

[1] Guntermann P, *et al.*: In situ calibration of heat meters in operation, *Euro Heat and Power*, 8 (2011), pp.46–49.

[2] Mori M, *et al.*: Development of a novel flow metering system using ultrasonic velocity profile measurement, *Experiments in Fluid*, 32 (2002), pp.153–160.

[3] Furuichi N: Fundamental uncertainty analysis of flowrate measurement using the ultrasonic Doppler velocity profile method, *Flow Measurement and Instrumentation*, 30 (2013), pp.202–211.

[4] Wada S and Furuichi N: Influence of obstacle plates on flowrate measurement uncertainty based on ultrasonic Doppler velocity profile method, *Flow Measurement and Instrumentation*, 48 (2016), pp.81–89.

[5] O. Bonnefous and P. Pesque: Time domain formulation of pulsed-Doppler ultrasound and blood velocity estimation by cross correlation, *Ultrasonic Imaging*, 8 (1986), pp.73–85.

[6] Ilmar A. Hein and William D. O'brien JR: Volumetric measurement of pulsatile flow via ultrasound time-domain correlation, *Journal of Cardiovascular Technology*, vol.8, No.4 (1989), pp.339–348.

[7] Ilmar A. Hein, *et al.*:A real-time ultrasound time-domain correlation blood flowmeter, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol.40, No.6 (1993), pp.768–775.

[8] Yamanaka G, *et al.*: Velocity profile measurement by ultrasound time-domain correlation method, *5th World Conference on Experimental Heat Transfer*, *Fluid Mechanics and Thermodynamics*, Thessaloniki, Greece, September 24-28, (2001-9), pp.1189–1193.

[9] Ozaki Y, *et al.*: High time resolution ultrasonic velocity profiler, *Exp Therm Fluid Sci*, 26 (2002), pp.253–258.

[10] DW Rickey *et al.*: A velocity evaluation phantom for colour and pulsed Doppler instruments, *Ultrasound in Medicine and Biology*, 18(5) (1992), pp.479–494.

[11] Jensen JA: Range/velocity limitations for time-domain blood velocity estimation, *Ultrasound in Medicine and Biology*, 19(9) (1993), pp.741–749.

[12] Skoink Mi: Introduction to radar system, 2nd ed., McGraw-Hill, 1983.

[13] Furuichi N, Terao Y and Takamoto M: Calibration facilities for water flowrate in NMIJ, *Proceedings of 7th International Symposium on Fluid Flow Measurement*, Anchorage, USA, August (2009), pp.12–14.

[14] Tezuka K, *et al.*: Assessment of effects of pipe surface roughness and pipe elbows on the accuracy of meter factors using the ultrasonic pulse Doppler method, *J. of Nuclear Science and Technology*, 45(4) (2008), pp.304–312.

[15] Wada S, *et al.*: Development of pulse ultrasonic Doppler method for flow rate measurement in power plant – Multilines flow rate measurement on metal pipe, *J. of Nuclear Science and Technology*, 41(3) (2004), pp.339–346.