10th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering
Tokyo Japan (28-30. Sep., 2016)

# Influence of velocity distribution on accuracy of transit-time ultrasonic flow meter

Ei Muramatsu[1], Hideki Murakawa[1], Daiki Hashiguchi[1], Hitoshi Asano[1],
Sanehiro Wada[2], Noriyuki Furuichi[2]

[1] Department of mechanical engineering, Kobe University, 1-1 Rokkodai, Nada, Kobe, 657-8501, Japan
[2] National Institute of Advanced Industrial Science and Technology, Tsukuba Central 3, 1-1-1 Umezono, Tsukuba, 305-8563 Japan

The transit-time 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. Velocity profile depends on not only Reynolds number but also the upstream condition and sensor pocket on the pipe wall. Therefore, on-site calibration is desirable by measuring velocity profile. In this study, a measuring system which can measure velocity profile using ultrasonic pulsed Doppler method and the transit time simultaneously was developed, and the simultaneous measurements were carried out. In the experiments, velocity profiles were distorted by installing an obstacle plate upstream of the test section and influence of the velocity profiles on accuracy of the TOF are discussed. As a result, error of the TOF is found to be 1% for axisymmetric flow and 4% for asymmetrical flow without calibration. However, if the TOF is calibrated by the velocity profiles obtained using the pulsed Doppler method, the error can be reduced to approximately 1%. Furthermore, fluctuations of the transit time are in good agreement with that of velocity profiles.

**Keywords:** Transit-time ultrasonic flow meter, Flow rate, Velocity profile, Ultrasonic pulsed Doppler method

## 1. Introduction

Transit-time ultrasonic flow meter (TOF) has been widely applied in industrial field due to its advantages, such as small pressure loss, applicability to opaque fluid and large diameter pipe. The TOF derives flow rate from the difference of the transit time of ultrasonic pulse which is related with the line-average velocity on ultrasonic path. Hence, velocity profiles are assumed and the profile factors which converts the transit time to the flow rate are calibrated under the ideal flow conditions. However, it is well known that the velocity profile changes by the upstream pipe layout, the Reynolds number and the inner pipe surface roughness, and so on. Furthermore, Cordova et al. [1] pointed out that sensor pockets on the pipe wall is considered to distort the velocity profile and degrade accuracy of the TOF. Since it is impossible to take into account all these influences for the profile factor, the calibration test in the actual field, called on-site calibration, is desired to be carried out by measuring the velocity profile in the pipe.

The ultrasonic pulsed Doppler method (UDM) derives velocity profile on the ultrasonic path from reflected signals on ultrasonic reflectors in the flow. Integrating the obtained velocity profile over the pipe, flow rate can be calculated. Therefore, even if velocity profile in the pipe is distorted, flow rate can be obtained accurately using multiple measuring lines [2]. Hence, a hybrid ultrasonic flow meter which calibrates TOF by using UDM has been proposed [3]. However, 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 [4,5].

In this study, a measurement system which can perform simultaneous measurement of velocity profile using the UDM and the transit time of ultrasonic pulse was developed, and influence of the velocity profile on accuracy of the TOF was investigated.

## 2. Measurement principles

### 2.1 Transit-time measurement

Measurement principle of the TOF is depicted in Figure 1. The $t$ means transit time of ultrasound between sensors in stagnant flow. If ultrasonic pulse is emitted from the upstream transducer, transit time is shortened to $t - \Delta t$ by the flow velocity. On the other hand, transit time from the downstream transducer is delayed to $t + \Delta t$. Relationship between the $\Delta t$ and the line-average velocity between sensors, $V_L$, is expressed as

$$V_L = \frac{c^2}{D\tan\theta}\Delta t \,. \tag{1}$$

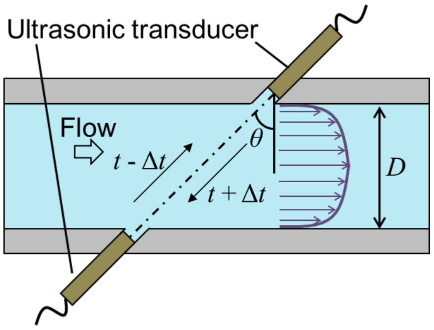


Figure 1: Measurement principle of the TOF

Where $c$, $D$, $\theta$ are the sound speed, the inner diameter of pipe and the contact angle of transducer, respectively.

Power-law velocity [6] is known as a velocity profile in fully-developed turbulent pipe flow and expressed as

$$U(y)=\frac{(n+1)(2n+1)}{2n^2}\frac{4Q}{\pi D^2}\left(\frac{2y}{D}\right)^{1/n}. \tag{2}$$

Where $U$, $y$, $Q$ denote the axial velocity component, the distance from the pipe wall and the flow rate, respectively. $n$ is a parameter that depends on the Reynolds number. Using Eq. (2), $V_L$ in the power-law velocity can be calculated as

$$V_L=\frac{4n+2}{n}\frac{Q}{\pi D^2}. \tag{3}$$

Since change of $n$ with Re is small, it can be said that $V_L$ is almost proportional to $Q$ if velocity profile is assumed to be power-law.

### 2.2 Ultrasonic pulsed Doppler method

In this study, velocity profile in a pipe is obtained by using the UDM. In the conventional UDM, maximum detectable velocity to flow direction, $U_{max}$, and the maximum measurable range from the sensor, $L_{max}$, are determined by the pulse emission interval, $T$, and expressed as

$$U_{max}=\frac{c}{4f_0T\sin\theta}, \tag{4}$$

$$L_{max}=\frac{cT}{2}\cos\theta . \tag{5}$$

Where $f_0$ is the basic frequency of the ultrasound. In order to obtain velocity profile over the pipe, $L_{max}$ should be larger than $D$. Hence, velocity profile cannot be measured under high flow-rate condition with the conventional method which employs single pulse emission interval.

In order to overcome this limitation, the authors developed a dealiasing method referred to as feedback method [4,5]. In the method, two pulse emission intervals, $T$ and $T+T_s$ are employed and the $U_{max}$ is expressed as

$$U_{max}=\frac{c}{4f_0T_s\sin\theta}. \tag{6}$$

Comparing Eqs. (4) and (6), the $U_{max}$ becomes $T/T_s$ times higher. Since the $L_{max}$ in the feedback method is the same with Eq. (5), higher velocity can be measured decreasing $T_s$. Using the feedback method, velocity profile under high flow-rate condition is obtained, and $V_L$ can be obtained from the velocity profile.

## 3. Measurement system and experimental facility

Developed measuring system consists 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 (AFG-2005, Good Will Instrument Co., Ltd.) and a personal computer. The measurement software is laboratory-made and developed using C++ and LabView (National Instruments Corp.). The function generator controls the pulse emission interval in the pulser/receiver. A couple of ultrasonic transducers are connected to the pulser/receiver. One transducer emits ultrasonic pulse and receives echo signals, and the other transducer receives transmitted ultrasonic pulse. Thus, both of 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). In this facility, flow rate is measured by using the weighing tank and its relative expanded uncertainty is 0.027%. Further details of the facility is described in [7]. Working fluid was water. Figure 2 shows the test section. Test section was horizontal pipe and its inner diameter, $D$, was 200 mm. A couple of transducers were set at $\theta = 45°$ and 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. The flow rate ranged from 80 to 500 $m^3/h$. Water temperature was at 20°C and $c$ = 1480 m/s. The measurement parameters of tabulated in Tables 1 and 2. For all conditions, $T$ was set at 0.5 ms. The spatial resolution along the measuring line, $\Delta L$, can be controlled by changing the number of cycles in an ultrasonic pulse. The $\Delta L$ was varied depending on the $Q$ because larger $\Delta L$ is required for measuring the higher velocity [4].

Table 1: Measurement parameters for symmetrical flow

| $Q$ | 81.7 $m^3/h$ | 162.0 $m^3/h$ | 321.1 $m^3/h$ | 500.6 $m^3/h$ |
|---|---|---|---|---|
| $\Delta L$ | 1.48 mm | 1.48 mm | 2.22 mm | 2.96 mm |
| $T_s$ | - | 0.167 ms | 0.083 ms | 0.071 |

Table 2: Measurement parameters for asymmetrical flow

| Q | 81.7 $m^3/h$ | 162.0 $m^3/h$ | 321.1 $m^3/h$ |
|---|---|---|---|
| $\Delta L$ | 1.48 mm | 1.48 mm | 2.96 mm |
| $T_s$ | 0.25 ms | 0.167 ms | 0.071 ms |

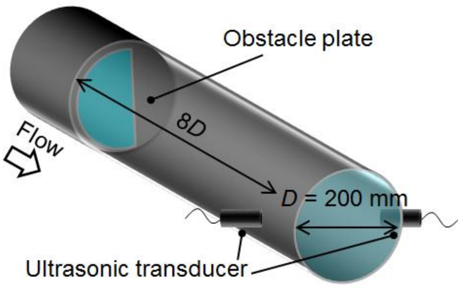
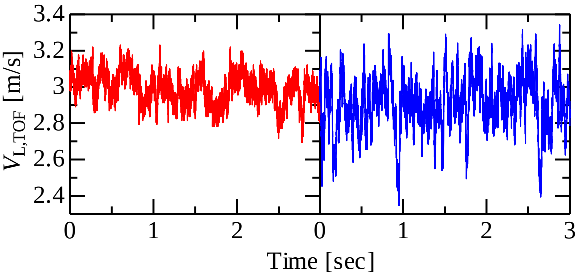


Figure 2: Layout of the test section



(a) Symmetrical flow (b) Asymmetrical flow

Figure 3: Time-series of $V_{L,TOF}$ at $Q$ = 321.1 m$^3$/h

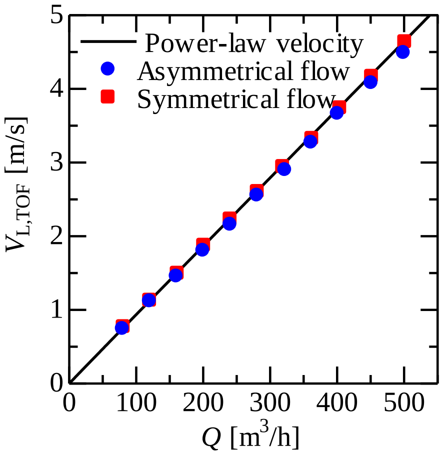


Figure 4: Comparisons between power-law and $V_{L,TOF}$

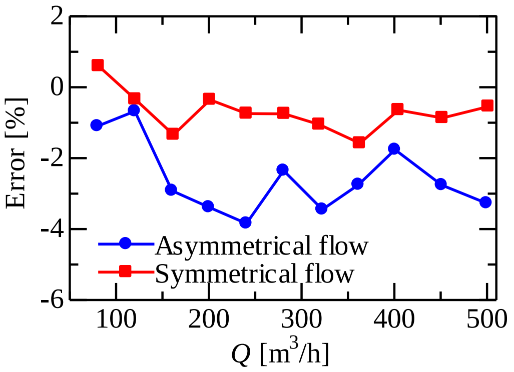


Figure 5: Error of $V_{L,TOF}$ for power-law velocity

Table 3: Standard deviations of $V_{L,TOF}$

| Q | Symmetrical flow | Asymmetrical flow |
|---|---|---|
| 81.7 m$^3$/h | 0.038 m/s | 0.095 m/s |
| 162.0 m$^3$/h | 0.058 m/s | 0.154 m/s |
| 321.1 m$^3$/h | 0.120 m/s | 0.211 m/s |

## 4. Results and discussions

### 4.1 Measurement results of TOF

$\Delta t$ was measured 1000 times, and line-average velocity, $V_{L,TOF}$, was calculated using Eq. (1) in each condition. Figure 3 shows time-series of $V_{L,TOF}$ in symmetrical and asymmetrical flow at $Q$ = 321.1 m$^3$/h. Although the flow rate was quite stable in this facility, $V_{L,TOF}$ fluctuated due to the turbulence in the flow. Standard deviations of $V_{L,TOF}$ were tabulated in Table 1. It can be said that if the velocity profile is distorted and/or flow rate is higher, the fluctuation become larger and the more number of $\Delta t$ should be measured for accurate measurement. Averaging 1000 $V_{L,TOF}$, time-average $V_{L,TOF}$ was calculated as shown in Figure 4. The solid line indicates Eq. (3). Although the $V_{L,TOF}$ was almost the proportional to $Q$, the errors between Eq. (3) and $V_{L,TOF}$ were several percent as shown in Figure 5. The errors for asymmetrical flow were larger than that for symmetrical flow, and its maximum value was 3.8%. It is because velocity profile in asymmetrical flow was distorted. In addition, maximum error was 1.6% for symmetrical flow. These errors were considered to be influence of the transducer pockets. Hence, even if the velocity profile in a pipe is considered to be fully-developed, the TOF may cause error up to 2%.

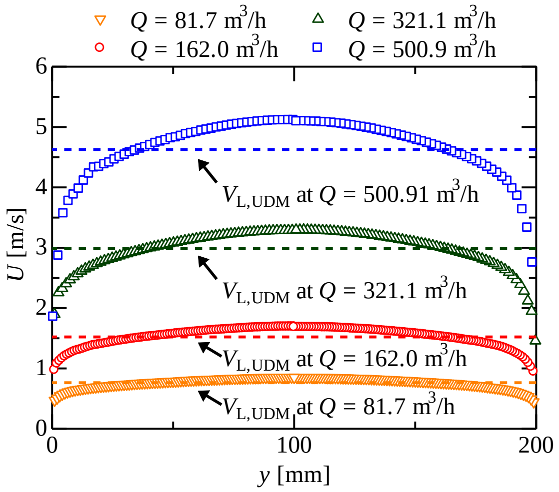
### 4.2 Velocity profile measurement

Time-average velocity profiles were calculated by averaging 1,000 velocity profiles measured by using the UDM. Measurement parameters are tabulated in Tables 2 and 3. Spatial resolution along the measuring line, $\Delta L$, was changed depending on the flow rate condition because larger $\Delta L$ is required for measuring the higher velocity [4]. $T_s$ was changed considering the flow velocity and Eq. (6). Although $U_{max}$ was 1.05 m/s in the conventional UDM, higher $U_{max}$ could be set using the feedback method. The results are shown in Figure 6. The line-average velocities calculated from the obtained velocity profiles, $V_{L,UDM}$, are also shown. It can be confirmed that velocity profiles were distorted by installing the obstacle plate. Velocity profile at $Q$ = 500.6 m$^3$/h for asymmetrical flow could not be measured due to its high turbulence. However, velocity profiles could be accurately measured in the other flow conditions using the feedback method.

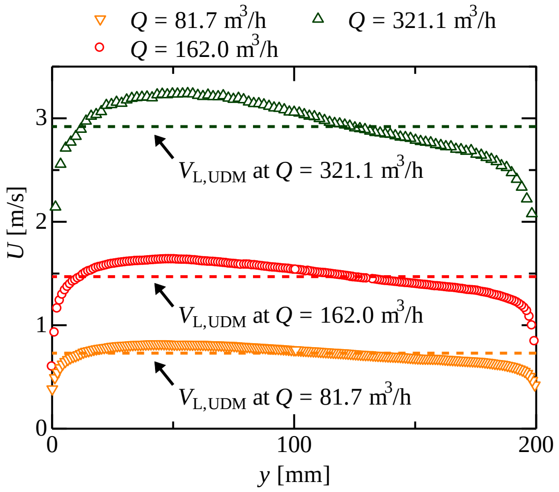
### 4.3 Comparisons of line-average velocities

The $V_{L,TOF}$ and $V_{L,UDM}$ were tabulated in Tables 4 and 5. Error between $V_{L,TOF}$ and $V_{L,UDM}$ were below 1% for symmetrical flow and below 2% for asymmetrical flow. Because Eq. (1) is well-established principle, these errors are considered to be caused by error in measured velocity profile by using UDM. However, calibrating the TOF by obtained velocity profile, error of the TOF can be improved particularly in distorted flow.

In order to evaluate relationship between the fluctuations of velocity profile and the transit time, time-series $V_{L,TOF}$ and $V_{L,UDM}$ were calculated at $Q$ = 321.1 m$^3$/h and shown in Figure 7. Temporal resolution of the UDM was 69 ms. For direct comparisons, moving average was applied for $V_{L,TOF}$. Tendencies of $V_{L,UDM}$ were in good agreement with that of $V_{L,TOF}$. Thus, Eq. (1) can be applied for such short time scale and simultaneous measurement of velocity profile and transit time is effective for evaluating the influence of transducer pocket.



(a) Symmetrical flow



(b) Asymmetrical flow

Figure 6: Time-average velocity profiles and $V_{L,UDM}$

Table 4: Comparisons VL for symmetrical flow

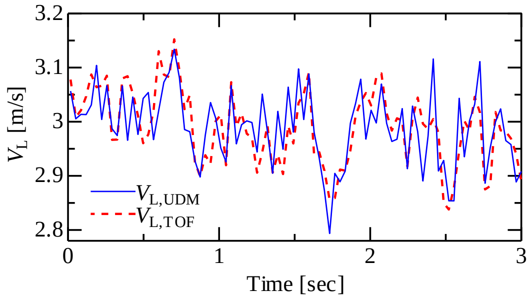
| $Q$ | 80.8 m$^3$/h | 162.0 m$^3$/h | 321.1 m$^3$/h | 500.6 m$^3$/h |
|---|---|---|---|---|
| $V_{L,UDM}$ | 0.75 m/s | 1.51 m/s | 2.98 m/s | 4.63 m/s |
| $V_{L,TOF}$ | 0.76 m/s | 1.50 m/s | 2.96 m/s | 4.64 m/s |
| Error | -0.87 % | 0.99 % | 0.63 % | -0.25 % |

Table 5: Comparisons $V_L$ for asymmetrical flow

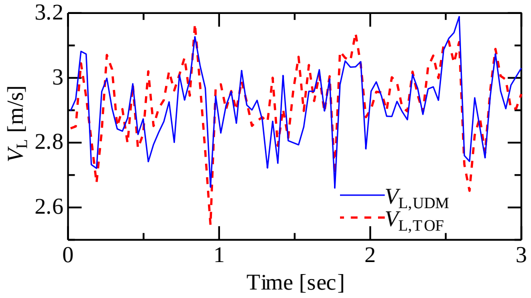
| $Q$ | 80.8 m$^3$/h | 162.0 m$^3$/h | 321.1 m$^3$/h | 500.6 m$^3$/h |
|---|---|---|---|---|
| $V_{L,UDM}$ | 0.74 m/s | 1.46 m/s | 2.92 m/s | - |
| $V_{L,TOF}$ | 0.75 m/s | 1.47 m/s | 2.88 m/s | 4.50 m/s |
| Error | -1.85 % | -0.34 % | 1.18 % | - |

## 4. Summary

In order to evaluate influence of velocity profile on accuracy of the TOF, a measuring system which can measure the velocity profile and the transit time of ultrasonic pulse simultaneously was developed. The simultaneous measurements were carried out for symmetrical and asymmetrical flows. Velocity profile was measured using the UDM. It was confirmed that without calibration, the TOF may cause the error of 1% even if pipe length at the upstream is sufficient. Furthermore, if the TOF is installed for distorted flow condition, the error may dramatically increase. However, it was shown that the TOF error can be reduced by on-site calibration using the UDM. In addition, line-average velocities obtained by using the TOF and the UDM in short time scale were also in good agreement.



(a) Symmetrical flow



(b) Asymmetrical flow

Figure 7: Results of simultaneous measurement of $V_L$ by using UDM and TOF for $Q$ = 321.1m$^3$/h

## References

[1] Cordova L, *et al.*: Qualification of an ultrasonic flow meter as a transfer standard for measurements at Reynolds numbers up to 4 × $10^6$ between NMIJ and PTB, Flow Meas. Inst.,45 (2015), 28-42.

[2] 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. Nucl. Sci. Technol., 41 (2004), 339-346.

[3] Tezuka K *et al.*: Ultrasonic pulse-Doppler flow meter application for hydraulic power plants, Flow Meas. Inst., 19 (2008), 155-162.

[4] Murakawa H *et al.*: A dealiasing method for use with ultrasonic pulsed Doppler in measuring velocity profiles and flow rates in pipes, Meas. Sci. Tech., 26 (2015), 085301, 11pp.

[5] Muramatsu E *et al.*: Multi-wave ultrasonic Doppler method for measuring high flow-rates using staggered pulse intervals, Meas. Sci. Tech., 27 (2016), 025303, 11pp.

[6] Davies, J.T., Turbulence phenomena, Academic Press, New York, 1972

[7] Furuichi N *et al.*: Calibration facilities for water flowrate in NMIJ, Proc of 7th ISFFM (2009), 7pp.