Accuracy enhancement of a combined V/Z clamp-on ultrasonic flow meter

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Abstract

Ultrasonic flow metering with clamp-on type transducers is a promising method when portability in flow metering is necessary. Nevertheless, the clamp-on ultrasonic flow meter has low measurement accuracy as flow speed in the pipe decreases. If the two types of clamp-on ultrasonic flow paths, namely, Z-shaped and V-shaped ultrasonic paths, are combined, measurement accuracy can be increased because the metering output becomes robust. In the present study, the measurement accuracy of the combined clamp-on ultrasonic flow meter was within ±2 % at 50 m^3/h, which was smaller than those of the Z-shaped and the V-shaped clamp-on ultrasonic flow meters at the same flow rate. This can provide an advantage for water resource management because a general guideline for the water resource management is less than ±2 %.

Introduction

Clamp-on ultrasonic flow metering is becoming a popular method for flow metering because of its portability. A clamp-on type ultrasonic flow meter (hereafter, a clamp-on UFM) can measure flow rates in a pipeline by attaching two ultrasonic transducers on the surface of the pipeline. Ultrasonic waves generated by the transducers are transmitted to the liquid flow in the pipe by penetrating the surface of the pipe according to the Snell's law. This makes handling of the clamp-on UFM easier than any other types of flow metering modalities. Therefore, one might consider the clamp-on UFM as an appropriate method to check the performance of flow meters in the pipeline.

However, the clamp-on UFM is not yet widely used in metrological purposes due to its low measurement accuracy. When the averaged flow speed in the pipe is more than 0.5 m/s, the measurement accuracy of the clamp-on UFM can be anticipated as low as ±1 %. But, when the averaged flow speed becomes less than 0.5 m/s, the measurement accuracy can be greater than ±2 %. Considering that the measurement accuracy of the electro-magnetic flow meters is less than ±0.5 % at low flow speed, the accuracy of the clamp-on UFM would not be desirable in using the flow meter as a check standard. In addition, the measurement accuracy is critical for environmental purposes. For example, a general guideline for water resource management is ±2 %. Therefore, various types of transducer arrangement should be devised to enhance the measurement accuracy of the clamp-on UFM.

As an attempt to find an efficient transducer arrangement, a method using three ultrasonic transducers is suggested in the present study. This method combines both the Z-shaped and the V-shaped ultrasonic paths to make flow rates robust to the flow unsteadiness in the pipe. With the combined method, inner pipe diameter can be estimated. Flow speed is calculated by averaging the flow speeds along the Z-shaped and the V-shaped ultrasonic paths. Then flow rate can by obtained by multiplying the averaged flow speed with the cross section area of the pipe. Therefore, this method needs not to measure the inner diameter of the pipe. Instead, this method requires temperature measurement to find out the sound speed of the fluid in the pipe.

This study begins with mentioning measurement principle of the clamp-on UFM. First, the Z-shaped and the V-shaped clamp-on UFM are considered with transit time correction. Then, the combined V/Z clamp-on UFM which combines between the Z-shaped and the V-shaped UFM is explained. After that, some experimental results performed in KRISS water flow standard system (hereafter, WFSS)

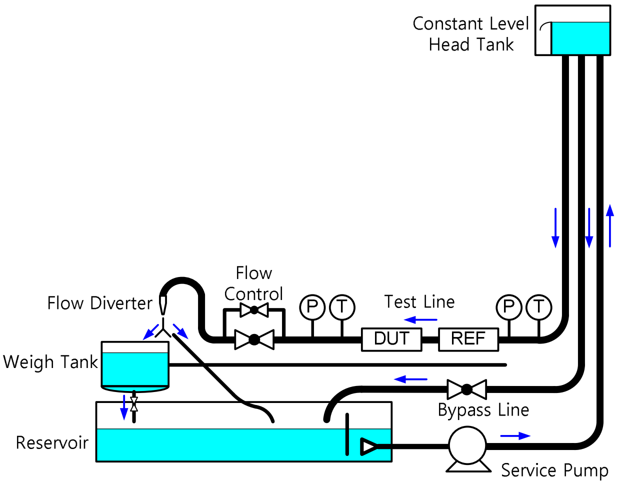

Figure 1. Schematic diagram of KRISS WFSS

are shown. Finally, some discussion regarding the combined V/Z clamp-on UFM is deployed.

Experimental Method

KRISS WFSS was utilized for measuring flow rates in a pipe flow [1, 2]. The WFSS provided steady flow condition in the range between 40 m^3/h and 400 m^3/h with expanded uncertainty less than 0.09% (k = 2) [3]. The WFSS consisted of a reservoir, a constant level head tank, a flow diverter and a weigh tank as shown in Fig. 1. The diameter of the main pipe was 259.4 mm (250A). An electro-magnetic flow meter (E+H promag 53W, hereafter, REF) was installed upstream of the clamp-on UFM (hereafter, DUT) to measure the reference flow rate.

Flow rate deviation between the REF and the DUT was obtained at five measuring points with five reproducible measurements.

$$F = \frac{Q_{DUT} - Q_{REF}}{Q_{REF}} \times 100 \ [\%] \qquad (1)$$

Here, Q_{DUT} is the flow rate indicated by the DUT and Q_{REF} is the flow rate indicated by the REF.

In the Z-shaped ultrasonic path, the transducer distance H can be corrected to H_1 by considering the ultrasonic path penetrating the transducer and the pipe.

$$H_1 = H - 2\left(d_1 \tan\theta_1 + d_2 \tan\theta_2\right) \qquad (2)$$

Here, d_1 is the location of a piezo actuator in the transducer, θ_1 is the incidence angle in the

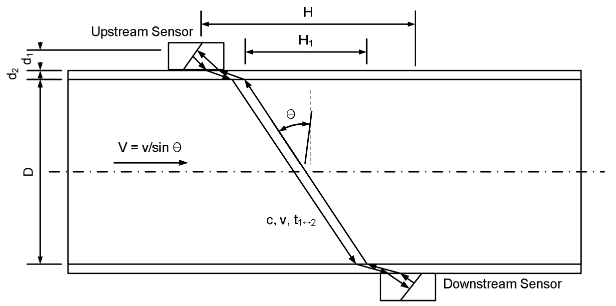

Figure 2. Z-shaped ultrasonic path in the clamp-on UFM

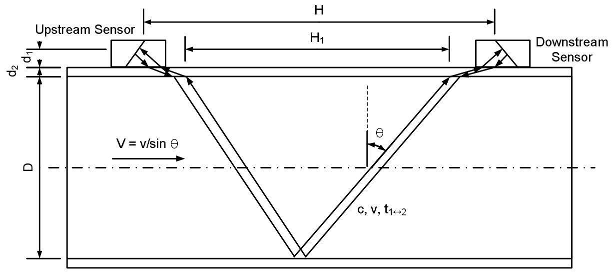

Figure 3. V-shaped ultrasonic path in the clamp-on UFM

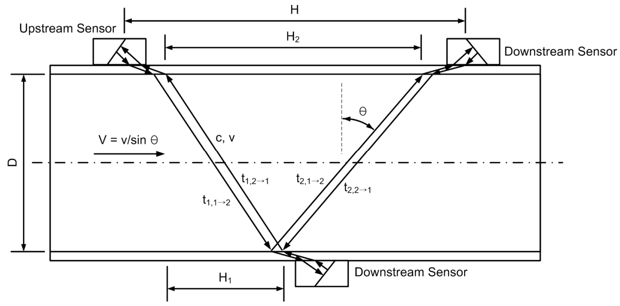

Figure 4. Ultrasonic path in the combined V/Z clamp-on UFM

transducer, d_2 is the thickness of the pipe, and θ_2 is the refraction angle in the pipe as shown in Fig. 2. Transit time between the two transducers can be corrected by the following equation.

$$\Delta t = \frac{1}{2}\left(\left(t_{1\to2} + t_{2\to1}\right) - 2A - \sqrt{\left(t_{2\to1} - t_{1\to2}\right)^2 + 4A^2}\right) \qquad (3)$$

Here, $t_{1\to2}$ is the transit time from transducer 1 to transducer 2, $t_{2\to1}$ is the transit time from transducer 2 to transducer 1 in Fig. 2. A is H / ($2c \sin\theta$), c is the sound speed of water and θ is the refraction angle of water. $t_{1\to2}$ and $t_{2\to1}$ can be corrected by subtracting Δt from both $t_{1\to2}$ and $t_{2\to1}$.

In the V-shaped ultrasonic path, the transducer distance H can be corrected to H_1 as suggested in Eqn. (2). The transit time between transducer 1 and transducer 2 can be also corrected by Δt.

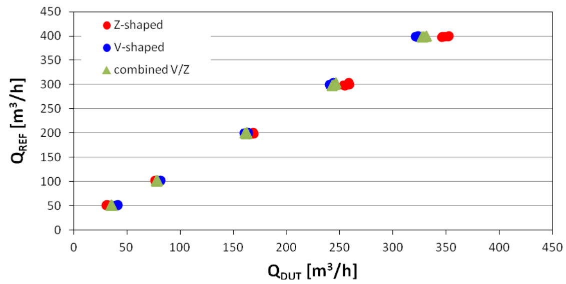

Figure 5. Experimental results of the clamp-on UFM before calibration

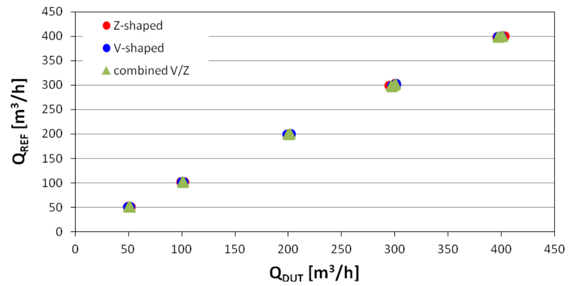

Figure 6. Experimental results of the clamp-on UFM after calibration

The combined V/Z clamp-on UFM utilizes the above equations to correct the transit time. In addition, the inner diameter of a pipe can be obtained by combining the corrected transit time and the transducer distance.

$$D = \sqrt{\left(c\left(t_{1\to 2} + t_{2\to 1}\right)/2\right)^2 - \left(H_2 - H_1\right)^2} \qquad (4)$$

According to the notations in Fig. 4, $t_{1\to 2}$ becomes ($t_{2,1\to 2}$ - $t_{1,1\to 2}$) and $t_{2\to 1}$ becomes ($t_{2,2\to 1}$ - $t_{1,2\to 1}$). Flow velocity in the pipe can be obtained by combining the velocities along the Z-shaped and the V-shaped ultrasonic paths.

$$v_1 = \frac{D}{2\cos\theta}\left(\frac{1}{t_{1,1\to 2}} - \frac{1}{t_{1,2\to 1}}\right) \text{ (Z-shaped)} \qquad (5)$$

$$v_2 = \frac{D}{\cos\theta}\left(\frac{1}{t_{2,1\to 2}} - \frac{1}{t_{2,2\to 1}}\right) \text{ (V-shaped)} \qquad (6)$$

$$v = v_1 + v_2 \qquad (7)$$

Therefore, the flow rate can be calculated according to the following equation.

$$Q_{DUT} = a\left(\frac{\pi D^2}{4}\frac{v}{\sin\theta}\frac{1}{K_{FPCF}}\right) + b \qquad (8)$$

Here, D is the pipe diameter, K_{FPCF} is the flow profile correction factor, both a and b are the calibration coefficients to Q_{DUT} [4, 5].

Experimental Results

Some of the experimental results of the clamp-on UFM are shown in Fig. 5. The magnitude of Q_{DUT} was less than that of Q_{REF}. This made the slope coefficient a in Eqn. (8) greater than 1 as indicated in Table 1. However, all the flow rates indicated by the three types of clamp-on UFM agreed well with each other as calibration was applied to the measurement data

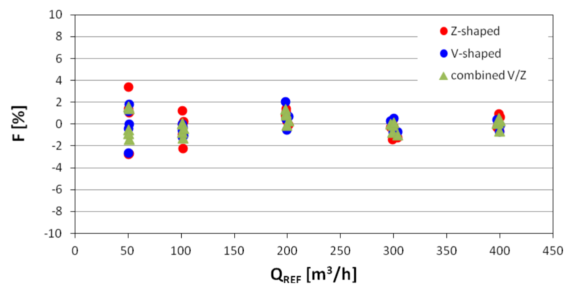

Figure 7. Flow rate deviation of the clamp-on UFM

	Z-shaped	V-shaped	combined V/Z
slope	1.099	1.233	1.186
Intercept [m³/h]	15.753	0.635	8.564

Table 1. Calibration coefficients of the clamp-on UFM

as shown in Fig. 6. The flow rate deviation F showed differences at low flow rate region in Fig. 7. For example, the Z-shaped and the V-shaped UFM showed measurement accuracy less than (-3 ~ 4) % and (-3 ~ 2) % at 50 m³/h, respectively. On the contrary, the combined V/Z clamp-on UFM showed the measurement accuracy of ±2 % at 50 m³/h. This means that an averaged value of the two flow rates by the Z-shaped and the V-shaped UFM, i.e., Eqn. (7), can produce flow rates robust to flow unsteadiness. This also means that the combined V/Z clamp-on UFM might be more appropriate than the Z-shaped or the V-shaped clamp-on UFM in water resource management.

The estimated inner diameter of the pipe was 258.15 mm, based on the difference of the transducer distance, 136 mm, and the water sound speed at 25 °C, 1,496 m/s [6]. Compared with the nominal inner diameter of 259.4 mm, the relative deviation was -0.48 %. Therefore, the accuracy of estimating the inner diameter of the pipe was about ±0.5 %.

The reason why the flow rate distribution by the combied V/Z clamp-on UFM becomes robust is because the interrogation areas for the Z-shaped and the V-shaped clamp-on UFM are different. This means that random effects due to various spatio-temporal characteristics of flow unsteadiness might be cancelled with each other at the low flow rate region due to different interrotation areas. However, this assumption was not yet proven in the present study. This will be taken as a future work.

Conclusions

A clamp-on ultrasonic flow meter with three transducers, named as a combined V/Z clamp-on UFM, was introduced to enhance the measurement accuracy of flow metering at low flow rate. The UFM combined both the Z-shaped and the V-shaped ulrtasonic paths to make the flow outputs be more robust to the flow unsteadiness. Toward this end, the ultrasonic wave propagation in the solid media was corrected. After that, two flow speeds from the Z-shaped and the V-shaped ultrasonic paths were averaged. Finally, the averaged flow speed was multiplied with the pipe cross-section area to calculate flow rate.

In a flow measurement experiment, the combined V/Z clamp-on UFM was compared with the Z-shaped and the V-shaped clamp-on UFMs. In the experiment, the measurement accuracy of the combined V/Z clamp-on UFM was within ±2 % at 50 m^3/h. However, the measurement accuracy of the Z-shaped and the V-shaped UFMs was (-3 ~ 4) % and (-3 ~ 2) %, respectively. Therefore, the accuracy enhancement of the combined V/Z clamp-on UFM could be found in this experiment. It was conjectured that the reason for the accuracy enhancement was due to the canceling effect of flow unsteadiness with difference interrogation areas between the Z-shaped and the V-shaped ultrasonic paths.

Acknowledgement

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