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Development of Multi-parallel-path Clamp-on Ultrasonic Flowmeter
クランプオン型平行多測線方式超音波流量計の開発

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1. Introduction

A clamp-on ultrasonic flowmeter measures the flow velocity in a pipe by installing sensors on the outside of the pipe and propagating ultrasonic waves through the pipe wall to the fluid inside (**Fig. 1**). Typically, a pair of sensors is placed so that the ultrasonic waves propagate on the path through the center of the pipe. However, since this method can only obtain the flow velocity on the diameter, measurement errors occur when the flow velocity distribution in the pipe is distorted.

On the other hand, the chordal method utilizes multiple parallel paths, including off-center paths of the pipe, and is expected to provide more accurate measurement even under the distorted flow velocity distribution. This method is used for high accuracy in wetted ultrasonic flowmeters where the sensor is directly inserted through a hole in the pipe. However, the clamp-on ultrasonic flowmeter requires ultrasonic waves to propagate in a path away from the center even though the ultrasonic waves are incident from outside the pipe, and the incident angle may exceed the critical angle. For this reason, the chordal method was not practical for clamp-on sensors.

In this paper, we describe the development of a clamp-on sensor with an incidence angle exceeding the critical angle, which can realize the chordal paths as shown in **Fig. 2**, and report the experimental results of flow measurement.

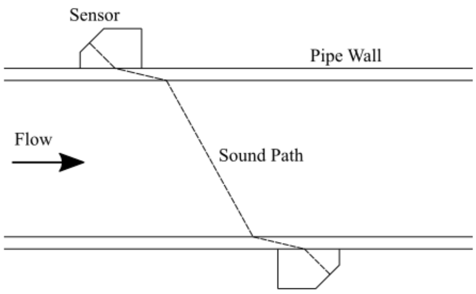

Fig. 1 Clamp-on ultrasonic flowmeter

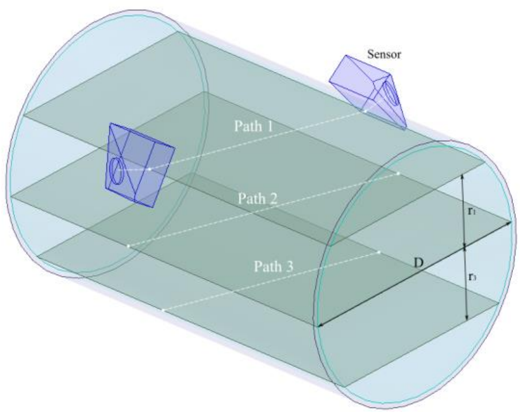

Fig. 2 Example of chordal paths. This figure shows three parallel paths with paths through the center and away from the center by r_1, r_3.

2. Sensor Design

In a transit-time ultrasonic flowmeter, the propagation path between the sensors requires a certain inclination angle from upstream to downstream in order to obtain the flow velocity in the pipe. Normally, a clamp-on ultrasonic flowmeter with a path through the center of the pipe uses an inclination angle of around 20°. However, if an off-center path of the pipe with the same inclination angle is used for chordal measurement, a larger refraction angle is required at the boundary to the fluid. For example, the sound velocity of water is about 1500 m/s and that of stainless-steel transverse wave is about 3100 m/s. Therefore, when using a propagation path that requires an underwater refraction angle of 29° or more, the angle of incidence from the sensor to the stainless-steel pipe wall exceeds the critical angle, resulting in total reflection. On the other hand, since evanescent waves are generated in the pipe wall at this time, ultrasonic waves may be transmitted into the water if the wall thickness is almost the same as the wavelength [1, 2].

In this study, we developed clamp-on sensors that realize two parallel paths at ±0.5R (R: pipe radius) from the center of the pipe. When the inclination angle of the path is set to 20°, the required underwater refraction angle for the 0.5R path is 35.5°. In this case, the material usually used for the wedge of the clamp-on sensor, such as polyetherimide, requires an incidence angle of more than 70° because the sound velocity is higher than that of water, which makes the sensor size large and difficult to design. As an alternative material, silicone rubber, which has the sound velocity of about 1000 m/s, was found to be suitable as the wedge material because the angle of incidence can be reduced to about 23°. Therefore, we made a prototype of the sensor as shown in **Fig. 3**, using silicone rubber as the wedge material. The target pipe size is DN 300mm, and the center frequency is 400 kHz.

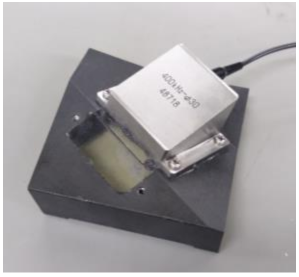

Fig. 3 Clamp-on sensor of ±0.5R paths

3. Experimental Results

We installed two pairs of the prototype sensors in the DN 300mm line (pipe wall thickness: 4.5mm) of the flow calibration facility as chordal paths of ±0.5R as shown in **Fig. 4**, and conducted flow measurement experiments. **Figure 5** shows the received waveform obtained from one of the sensor pairs. The travel time of the received wave is almost the same as the time expected from the 0.5R path. Thus, it is confirmed that the ultrasonic wave propagates along the desired path and the received waveform can be clearly obtained.

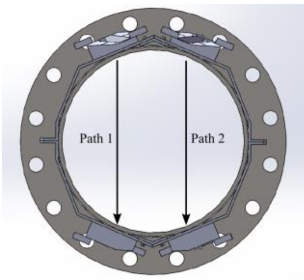

Fig. 4 Installation of the chordal sensors

Next, the sensors were installed at a position taking 50 times the straight pipe length of diameter (50D) from a sensor toward upstream, where the distortion in the flow velocity distribution was small. Then, the flow measurement was performed with the flow velocity in the pipe set to 2 m/s. As a comparison, conventional clamp-on sensors using a path through the center of the pipe were installed at the same time, and 9 cycles of 2-minutes measurement were performed. The measurement

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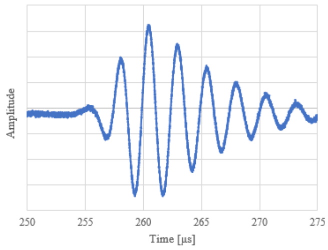

Fig. 5 Received wave

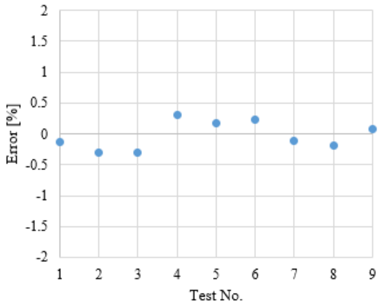

Fig. 6 Measurement errors of the chordal sensors against the average measurement of the conventional sensors

errors of the chordal sensors compared to the average measurement of the conventional sensors are shown in **Fig. 6**. The results show that the chordal sensors agree with the result of conventional sensors within ±0.5% measurement deviation even though they use the paths of ±0.5R, indicating that they can perform flow measurement with equivalent accuracy. Therefore, it is confirmed that the clamp-on ultrasonic flowmeter can realize the chordal measurement using the off-center path of the pipe.

4. Conclusion

In this paper we presented the development of the chordal clamp-on ultrasonic flowmeter. Verifying the received waveform and flow measurement accuracy, we have realized a clamp-on ultrasonic flowmeter using the ±0.5R paths and confirmed that it can measure with the same accuracy as conventional sensors in a fully developed flow. Therefore, we consider that the clamp-on ultrasonic flowmeter can also realize more accurate measurement using chordal method. In future work, we will verify the accuracy of the chordal clamp-on ultrasonic flowmeter by conducting measurements under distorted velocity distribution.

References

1. K. Shimizu, et al.: IEICE Tech. Rep., vol. 115, no. 423 (2016) 1-5.
2. T. Hayashi, et al.: Proc. Symposium on Ultrasonic Electronics, vol. 37 (2016) 1P2-7.