A Study on Ultrasonic Wave Detection Method for Clamp-on Ultrasonic Gas Flowmeter

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Abstract: We examine clamp-on ultrasonic flowmeters for gas, in particular, low-pressure gases at atmospheric pressure. For clamp-on ultrasonic flowmeters, the ultrasonic wave is generated outside the plumbing, transmitted into the gas inside the plumbing, and received on the outside of the plumbing. In this situation, specific acoustic impedances differ greatly for the gas and the metallic plumbing. Therefore, it is necessary to transmit and receive ultrasonic waves efficiently. In addition, separation of two routes of ultrasonic waves is important—those transmitted to the internal gas in a straight route and those transmitted to the metallic plumbing in a circuitous route. We transmitted and received ultrasonic waves aslant to the plumbing using an ultrasonic transducer, which had a curvature corresponding to the radius of the metallic plumbing. Moreover, we were able to separate the ultrasonic wave propagating in the gas and the metallic plumbing. We verified the signal transmitted inside of the gas clearly, with approximately 4 times the signal-to-noise ratio. Therefore, we have acquired useful data for the development of clamp-on ultrasonic flowmeters for low-pressure gases.

Key Words: ultrasonic flowmeter, clamp-on, gas-flow, time-difference method.

1. Introduction

Energy conservation is an important problem in society. In Japan, since the electric power supply in the summer is insufficient, reducing energy consumption is an important problem. In particular, energy conservation in office buildings and factories is required. To reduce energy consumption efficiently, energy management needs to be considered [1]. For energy management, consumed energy can be measured using various kinds of sensors, and the total amount of energy consumption can be reduced [2]. At factories or office buildings, various types of energies such as electric and gas energy are consumed. The consumption of electric energy is easily measurable using a clamp meter without wiring work. In contrast, to measure the consumption of gas energy, gas plumbing process is necessary to install a flowmeter. However, processing gas plumbing can be difficult due to possible gas leaks. Therefore, a method to measure the gas flow rate without plumbing processing is desired.

There are several methods to measure the gas flow rate [3]. These include Karman vortex flowmeters, electromagnetic flowmeters, and ultrasonic flowmeters. We research flow-rate measurements using ultrasonic waves. Generally, an advantage of flow-rate measurement by ultrasonic waves is that it does not result in a pressure loss. Various approaches of flow-rate measurement using ultrasonic waves exist. For example, simple measurement of the liquid flow rate through plumbing has been studied [4],[5]. Flow rate measurements using ultrasonic waves in open channels have also been performed [6],[7]. Non-contact flow-rate measurement has also been attempted [8]. Moreover, ultrasonic waves have been used to detect vortices within the plumbing [9], and the detection in Karman vortex flowmeters [10],[11]. In this paper, we research the most common ultrasonic flowmeter that measures the flow rate in plumbing.

There are two types of ultrasonic flowmeters that measure a fluid flow through plumbing. One is an in-line ultrasonic flowmeter, and the other is a clamp-on ultrasonic flowmeter [3]. For an in-line type ultrasonic flowmeter, ultrasonic probes are installed in the inside of the plumbing. Therefore, to measure the flow rate, a plumbing process is necessary. For a clamp-on ultrasonic flowmeter, the ultrasonic probes are placed on the outside of the plumbing. Therefore, a plumbing process is not necessary, and the clamp-on ultrasonic flowmeter can measure the flow rate easily.

However, while the clamp-on ultrasonic flowmeter for liquids is popular, there are scarcely any clamp-on ultrasonic flowmeters for gas. In particular, there are no clamp-on ultrasonic flowmeters that can measure low-pressure gas at atmospheric pressure. A clamp-on ultrasonic flowmeter inputs an ultrasonic wave from the outside of the plumbing, and detects it on the outside. Therefore, a method that detects ultrasonic waves efficiently is required.

This study reports an ultrasonic detection method for a clamp-on ultrasonic gas flowmeter. The detection method in this paper is an important technology in the development of clamp-on ultrasonic flowmeters for gas.

The outline of this paper is as follows. In Section 2, we explain the measurement principle of clamp-on ultrasonic flowmeters and the problem of gas measurement. We explain the experiments and experimental results in Sections 3 and 4. In Section 5, we discuss the focusing and separation of ultrasonic waves to detect the ultrasonic wave which propagates in
the internal gas. Finally, conclusions are drawn in Section 6.

2. Method

Clamp-on ultrasonic flowmeters are widely used to measure the flow rate of liquids [12]. The propagation time difference method is generally used for liquid flow-rate measurement. We explain the measurement method of the propagation time difference method using the schematic diagram shown in Fig. 1.

In a clamp-on ultrasonic flowmeter, a pair of ultrasonic probes is installed onto the plumbing. The two ultrasonic probes are placed so that the ultrasonic wave propagates aslant to the gas flow direction. The ultrasonic wave is generated from one ultrasonic probe and received by the other. The generated ultrasonic wave penetrates the metallic plumbing, propagates through the internal gas, penetrates the metallic plumbing again, and is received by the other ultrasonic probe. While an ultrasonic wave generated from the upstream side is accelerated in its path to the other probe, that generated from the downstream side is decelerated in its path to the other probe. Therefore, a propagation time difference occurs, which depends on the flow velocity of the fluid inside the plumbing. By measuring the propagation time difference, the flow velocity can be determined.

For gas clamp-on ultrasonic flowmeters, the specific acoustic impedances of metallic plumbing and internal gas differ greatly, which is a problem. The specific acoustic impedances of metal and gas are as follows [13].

Specific acoustic impedance of steel: 46.4 (Pa·s/m)
Specific acoustic impedance of air: 0.000428 (Pa·s/m)

That is, the acoustic impedances between steel and air differ by approximately 10,000 times. Therefore, most ultrasonic waves will be reflected at the boundary of the plumbing and the gas. The reflected ultrasonic wave then propagates in the direction of the circumference of the plumbing, with repeating reflection within the metallic plumbing.

The reflected ultrasonic waves extend to the other ultrasonic probe. This causes a large amount of noise for gas clamp-on ultrasonic flowmeters. A diagram of this noise wave is shown in Fig. 2. Since specific acoustic impedances differ greatly between metals and gases, most reflected ultrasonic waves reach the other ultrasonic probe without decreasing. An ultrasonic wave propagated in the steel plumbing is larger than that propagated through the internal gas. It then becomes impossible to differentiate an ultrasonic wave that propagated through the internal gas from the large plumbing ultrasonic wave. This is a significant problem for gas clamp-on ultrasonic flowmeters.

As a method corresponding to this, Sasaki et al. have proposed applying a sound absorbing material on the outside of the plumbing to reduce the plumbing ultrasonic wave [14]. However, at actual measurement sites, it may be difficult to lay a sound absorbing material by the lagging materials or the surface state of the plumbing. Meanwhile, Kawaguchi et al. have proposed suppressing the plumbing noise by using an ultrasonic transducer with curvature [15]. However, they input ultrasonic waves perpendicularly to the plumbing and attempted flow-rate measurements using a shifting method. Their shifting method requires three transducers to receive the ultrasonic wave. Conversely, the propagation time difference method requires only one transducer to receive the ultrasonic wave. Therefore, their measurement system is complicated compared with the propagation time difference method.

We study gas flow-rate measurement using the propagation time difference method. In this paper, we investigate the ultrasonic wave detection method for a clamp-on ultrasonic gas flowmeter.

3. Experiments

The ultrasonic probes we made are shown in Fig. 3. The transducer was made of a composite material and is 14 mm wide and 30 mm long. It is curved to follow the curvature of the plumbing. To generate ultrasonic waves, we used seven burst waves at 1 MHz. We used burst ultrasonic waves to increase the signal intensity. We used 1 MHz ultrasonic wave because we thought that it was suitable if the wavelength is similarly the same as the length of the plumbing wall thickness. The input burst wave is shown in Fig. 4. When the probes are set face to face, the received ultrasonic waveform is shown in Fig. 5. Since the burst wave is input, the oscillation of the received wave continues for a while. For comparison, we also used a normal probe with a plane transducer. The aslant wedge was used to shoot an ultrasonic wave aslant. The aslant wedge was made of polystyrene. The angle of aslant wedge was 45 degrees to the straight side of the plumbing. The arrangement of the plumbing and ultrasonic probes is shown in Fig. 6.

The experimental setup is shown in Fig. 7. We applied voltage to the ultrasonic transducer using pulser circuitry and generated the ultrasonic waves. The plumbing was made of
The outer diameter was 60.5 mm, the wall thickness was 3.8 mm. The inner diameter was 52.9 mm. The received signal at the ultrasonic transducer was amplified and observed by a digital oscilloscope (Pico-scope 3205A). The experiments were conducted in a room. Atmospheric pressure air existed in the plumbing and the temperature of air is approximately 20°C. In this experiment, we generated no flow in the internal gas.

We will now explain the ultrasonic wave propagation which we consider in this experiment. Figure 8 shows the straight side cross-section of the plumbing and the schematic figure of the ultrasonic propagation. We explain the ultrasonic propagation using Snell’s law. In Fig. 8, \( \alpha \) and \( \beta \) are the incident angles of the ultrasonic wave. The sound velocities are as follows [12].

\[
\begin{align*}
V_w & : 2350 \text{ m/s,} \\
V_p & : 3251 \text{ m/s,} \\
V_g & : 344 \text{ m/s}
\end{align*}
\]

- \( V_w \): Sound velocity of aslant wedge (Polystyrene, Longitudinal wave)
- \( V_p \): Sound velocity of plumbing (Steel, Transverse wave)
- \( V_g \): Sound velocity of gas (Air, 20°C)

Initially, the ultrasonic wave generated from the probe propagates in the aslant wedge made of polystyrene. The longitudinal ultrasonic wave enters at 45° into the plumbing. The ultrasonic wave is refracted on the boundary of the aslant wedge and the plumbing. When the ultrasonic wave is refracted, the ultrasonic wave changes its mode to a transverse wave from a longitudinal wave. The ultrasonic wave is refracted following Snell’s law.

\[
\frac{\sin \alpha}{V_p} = \frac{\sin \beta}{V_g}
\]

From Eq. (2), \( \beta = 6.0° \). The ultrasonic wave enters the internal gas at 6.0°.

At the opposite side of the plumbing, the ultrasonic wave propagates similarly from the gas to the plumbing and to the wedge. Finally, the ultrasonic wave is received by the opposite side probe.

4. Results

Figure 9 shows the ultrasonic waveform observed by the ultrasonic transducer with curvature. To separate the ultrasonic wave that propagates through the plumbing from the ultrasonic wave that propagates through the internal gas, we used an obstruction. The waveform with the obstruction is shown in Fig. 10. The method using an obstruction is shown in Fig. 11.

As shown in Fig. 11, we inserted an obstruction (cardboard) into the plumbing due to which we were able to block just the ultrasonic wave propagated through the internal gas. The disappearance of the ultrasonic wave at Region A in Fig. 10, compared with Fig. 9, indicates the ultrasonic wave that propagated in the internal gas. When a curvature ultrasonic probe was used, the ultrasonic wave signal transmitted in the internal gas was
clearly detected. In Region A, when the signal intensity in Fig. 9 is compared with the surrounding noise level, there is an approximately 4 times the signal-strength difference. When detecting ultrasonic wave signals using a trigger, this is a sufficient level of signal-to-noise ratio. Therefore, we have detected the ultrasonic wave signal which propagates the internal gas by a sufficient signal-to-noise ratio.

For comparison, the waveform that used the plane transducers is shown in Fig. 12. Moreover, Fig. 13 shows the waveform with an inserted obstruction in the waveform of Fig. 12. When Fig. 13 is compared with Fig. 12, there is scarcely any change in the ultrasonic waveform. This indicates that the ultrasonic wave signal which transmits in the internal gas was not detected.

These results show that the ultrasonic wave which propagates the internal gas was significantly detected using ultrasonic transducers with curvature.

5. Discussion

5.1 Focusing of the Ultrasonic Wave

We now discuss the focal condition of the ultrasonic wave in the direction of the cross-section of the plumbing. In our experiments, we generated ultrasonic waves with a curved transducer. If the ultrasonic wave is aslant input into the plumbing, the ultrasonic wave is easily reflected at the boundary of the plumbing and gas to the surroundings direction of plumbing wall. By inputting the ultrasonic wave perpendicularly, the ultrasonic wave is input into the internal gas efficiently. To input the ultrasonic wave perpendicularly, the transducer was curved. Since the curvature of the transducer was the same as the curvature of the plumbing, the ultrasonic wave focused on the center axis of the plumbing. We checked the focal condition of the ultrasonic wave as follows.

We inserted an obstruction (a steel pipe) into the central axis of the plumbing, and then we checked whether the ultrasonic wave really focused on the axis of the plumbing. A schematic view of this method is shown in Fig. 14, and photographs are shown in Fig. 15. The outside diameter of the steel pipe was 7 mm. The ultrasonic waveform when the obstruction was placed at the central axis of the plumbing is shown in Fig. 16 (a). Figure 16 (b) shows the ultrasonic waveform when the offset was 5 mm from the central axis. By comparing Fig. 16 (a) and Fig. 16 (b), Region A is observed to be an ultrasonic wave signal that propagates in the internal gas. These experimental results show that the ultrasonic wave propagated in the 5 mm inner side from the central axis of pulping. We can verify that the ultrasonic wave was focused at the axis of the plumbing.
5.2 Ultrasonic Wave Separation

We input the ultrasonic wave into the plumbing efficiently using the curved transducer. However, we tried to shoot the ultrasonic wave aslant in the straight side cross-section, it was impossible to completely suppress a reflection of the ultrasonic wave at the boundary of the plumbing and inner gas. The ultrasonic wave reflected on the boundary and spread into the plumbing. Since the difference between the specific acoustic impedances of gas and metal is large, most of this reflected wave continued to exist in the plumbing. The ultrasonic wave that spread in the plumbing was larger than the ultrasonic wave that propagated in the internal gas. Therefore, separation of the two ultrasonic waves is important.

The sound velocities differ greatly in the metallic plumbing and the inner gas. Sound velocities differ greatly as follows [12].

The sound velocity of steel: 5,941 m/s (longitudinal wave)
The sound velocity of air: 344 m/s (20°C)

Moreover, in this study, we shot the ultrasonic wave aslant. By the difference in the sound velocities and the shooting of the ultrasonic wave aslant, the signal and the noise can be separated. We explain the separation of the ultrasonic waves using Fig. 17.

When the ultrasonic wave is shot from the outside of the plumbing, reflection and refraction occur at the boundary surface of the plumbing and the inner gas. Compared with gas, the sound velocity of steel is approximately 17 times higher. Therefore, the ultrasonic wave in the steel plumbing reaches the probe on the other side faster than the wave propagating through the inner gas. This is observed in Region A of Fig. 17. Next, the ultrasonic wave that propagated slowly through the gas is observed in Region B of Fig. 17. Since the sound velocities differ greatly between steel and gas, it is possible to separate the ultrasonic waves in the plumbing and gas. Finally, at the plumbing end, the ultrasonic wave that propagated inside the plumbing is reflected and returned to the receiver transducer. This is observed in Region C of Fig. 17.

The propagation time of the ultrasonic wave calculated from the sound velocity of steel in the metal plumbing is approximately 20 μs. The propagation time of the ultrasonic wave in the gas calculated from the sound velocity of gas is approximately 160 μs. Therefore, the signal that propagates through the internal gas will be detected with a lag of approximately...
140μs. From the experimental result of Fig. 17, the difference in the arrival time of ultrasonic waves A and B is approximately 140μs. This result is the same as the time difference calculated from the sound velocities.

Moreover, Region C is a reflected wave from the plumbing end. If the distance from the probe to the plumbing end is kept apart enough, this reflected wave is separable. In this case, the propagation time of the ultrasonic wave signal that propagates through the internal gas is 160μs. The transient time of the ultrasonic wave reflecting at the end of the plumbing should be longer than 160μs. The sound velocity in steel is 5,941m/s. The required separation distance is then calculated to be 475mm as following equation: 5,941 m/s × 160 μs/2 = 475 mm.

Therefore, the ultrasonic wave signal of region B is separable from the reflected wave of region C.

Therefore, we succeeded in separating the ultrasonic waves in the inner air and the plumbing, and the ultrasonic wave signal that propagates through the inner gas can be clearly observed, as shown in Fig. 17.

Even if a different gas is used, we can separate the ultrasonic waves in a similar manner. For example, the sound velocity of methane is slightly higher than that of air (air: 344 m/s, methane: 455 m/s). However, compared with the sound velocity of metal, the difference with this type of gas is not so large. Even if the type of metal plumbing is changed, we can separate the ultrasonic wave using the same logic. With a plastic plumbing such as polyethylene plumbing, there is practically no problem posed by a clamp-on ultrasonic flowmeter because the specific acoustic impedance difference is not as large as in metal.

6. Conclusion

In this study, we proposed an ultrasonic detection method using a clamp-on ultrasonic flowmeter for gas. We shot the ultrasonic wave aslant from the outside of the plumbing at atmospheric air exists. We succeeded in detecting the ultrasonic wave which transmits the internal gas using ultrasonic transducers with curvature. We verified that the ultrasonic wave was focused by the curved transducers at the plumbing center axis. By shooting an ultrasonic wave aslant, we were able to separate the ultrasonic wave which propagated in the inner gas and that propagated in the plumbing. We were able to verify that the ultrasonic wave signal which propagated the internal gas was 4 times the signal-to-noise ratio. When detecting an ultrasonic wave signal by a trigger, this is a sufficient level of signal-to-noise ratio. For the final development of a clamp-on ultrasonic flowmeter for low-pressure gas, further study is necessary. For instance, it is required to measure the ultrasonic propagation time shift when the gas is flowing. We are currently studying a measurement method for this propagation time shift. However, for the development of an ultrasonic gas flowmeter, it is very important to detect the ultrasonic wave from outside the plumbing. Therefore, the results of this paper are very useful toward the development of a clamp-on ultrasonic gas flowmeter.

References

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