Trans. of the society of instrument
and Control Engineers
Vol.E-2,No.1,160/164(2002)

Sensor Configuration and Flow Rate Characteristics of Ultrasonic Flowmeter for Very Low Liquid Flow Rate

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In this study, small disk ultrasonic transducers were used to develop a very small ultrasonic flowmeter with a pipe diameter of 0.53 mm ID. The feasibility of using a practical ultrasonic flowmeter to measure a liquid flow rate below 1 mL/min was investigated experimentally.

The minimum flow rate of an ultrasonic flowmeter depends on the resolution of the transit time measurement and the zero flow rate stability. The former can be improved by applying the high measurement resolution of propagation time of an ultrasonic pulse with advanced electronics. However, the latter gives rise to a serious problem for low flow rate measurements. One of the causes of the zero flow rate instability is that the superposition of reflected pulses or remaining pulses affects the main pulses. This problem can be easily avoided by carefully selecting the sensor material or appropriate sensor location. The other cause of the zero flow rate instability is the different thermal characteristics of the two sensors. In order to solve the above problem, in this study, a newly designed ultrasonic flowmeter was developed.

A glass tube was used as the measuring pipe of an ultrasonic flowmeter. Detected signals of ultrasonic pulses were processed by applying the zero-cross method and the cross-correlation method for comparison. The performance of the developed ultrasonic flowmeter was examined, in particular, the measurement resolution and the zero flow rate stability were carefully evaluated. Results of the flowmeter calibration were scattered within the range predicted from its measurement resolution. It shows that the flow rate more than 0.2 mL/min can be measured by the developed flowmeter. This suggests to be able to measure a very low flow rate range useful for semiconductor, medical and chemical industries.

Key Words : ultrasonic flowmeter, very low liquid flow rate, zero point stability, cross correlation, small disk ultrasonic transducer

1. Introduction

An ultrasonic flowmeter has the advantages of high response and no contact with working fluids, compare with others. The reliability of ultrasonic flowmeters has been greatly improved by recent rapid developments in electronics, and they are increasingly used for not-very-low-liquid or gas flow rate measurements in many industries [1)-4)].

With the progress of high integration of LSI devices, a demand for very low flow rate measurements increases to improve the efficiency of manufacturing process on semiconductor industry. However, thermal flowmeters or differential-pressure flowmeters, which have been conventionally used for such a purpose, have drawbacks in the low flow rate measurements and the long-term stability. The diameter of the pipe used in conventional ultrasonic flowmeter is still too big to measure low flow rate.

Generally, the minimum size of measuring pipe for ultrasonic flowmeters has been limited to some ten millimeters in diameter because of the difficult mounting of ultrasonic sensors to the small pipes and the insufficient resolution of ultrasonic transit time. Furthermore, unavoidable zero drift reduces the relative accuracy in the region of low flow rates.

In this study, the authors have developed a very small ultrasonic flowmeter to have improved above problems. They used a measuring pipe less than 1 mm in diameter passed through the center of small disk ultrasonic transducers. To minimize the zero drift and improve resolution, they employ a common receiving sensor and a new signal processing using a cross-correlation method. The feasibility experiment shows that the newly designed ultrasonic flowmeter can measure a liquid flow rate below 1 ml/min. This result suggests that the developed ultrasonic flowmeter is useful for applications in semiconductor industry.

2. The experimental setup

2-1 The test facility and the test method

The piston prover system was developed to generate the reference flow rate and was used for the calibration of the developed ultrasonic flowmeter. The schematic diagram of the facility is shown in Figure 1. The system uses two piston rods (6 mm in diameter and 300 mm in length) which are actuated by a servo system controlled by a PC and are used alternately to calibrate efficiently while one rod discharges, the other charges. The developed ultrasonic flowmeter was calibrated in the flow rate range between 0.2 and 1.6 ml/min. The reference flow rate was controlled by the revolution speed of the servo motor that was calibrated in advance by a gravimetric method, and the ultrasonic flowmeter was calibrated after the flow rate was stabilized. The ultrasonic flowmeter was tested using pure water in an air conditioned room at 22 ± 1 degrees.

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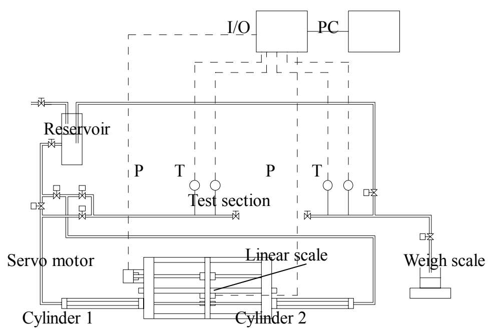

Fig.1. The schematic diagram of experimental apparatus

2-2 Calibration of the test facility

The test facility was calibrated by a gravimetric method applying dynamic weighing principle based on ISO 4185 and the measurement uncertainty of the facility was roughly estimated. The calibration was performed from measurements of the mass of the water collected by a beaker, collection time, temperature and pressure during the piston rod traveling 100 mm in length. The mass was measured using an electric balance. Data acquisition of the mass and the position of the piston rod were performed by a PC. The beaker was covered to minimize the measuring error of the mass due to vaporization of water, thus such error is thought to be very small and is neglected here.

The volumetric flow rate Qr that is calibrated by a gravimetric method is given by equation (1).

$$Q_r = \frac{\Delta w}{\rho \Delta t} \tag{1}$$

Where, Δw is the mass collected by a beaker, Δt is the collection time and ρ is the density of water.

The relative combined standard uncertainty of equation (1) is given by equation (2).

$$\left(\frac{u_c(Q_r)}{Q_r}\right)^2 = \left(\frac{u(\Delta w)}{\Delta w}\right)^2 + \left(\frac{u(\Delta t)}{\Delta t}\right)^2 + \left(\frac{u(\rho)}{\rho}\right)^2 \tag{2}$$

Where, $u_c(Q_r)$ is the combined standard uncertainty and u is the standard uncertainty of each uncertainty factor.

In this calibration, the speed of data acquisition by the PC was not fast enough for dynamic weighing of the mass. Therefore, the major uncertainty factors are Δw and Δt. The collection of mass by a beaker during the piston rod traveling 100 mm in length is about 2.8 g and the relative standard uncertainty is between 0.05 to 0.1 %. The traveling time of the piston rod for the distance of 100 mm depends on the speed of the piston rod, between 850 s at 0.2 mL/min to 100 s at 1.6 mL/min. The faster the speed of the piston rod, the larger delay of the data acquisition by the PC and the larger the relative standard uncertainty of the time, from 0.01 to 0.06 %.

Tables 1 and 2 show the results of calibration using each piston rod. Measurements were repeated 8 times at each motor revolution speed. The tables show the flow rates calculated from equation (1) at various motor revolution speeds and their relative combined standard uncertainties calculated from equation (2). Error factors of buoyancy correction, dead weights of the balance and effects of temperature are very small compared to the major uncertainty factors and they can be neglected here. Therefore, the relative combined standard uncertainty of the test facility is roughly estimated as being between 0.04 and 0.13 % depending on the flow rate and the piston rod. The expanded uncertainty of the test facility is less than 0.26 %, which is thought to be acceptable for the calibration of the developed ultrasonic flowmeter. However, the data acquisition system is being improved to minimize the uncertainty.

Table 1. Flow rates and their relative combined standard uncertainties by piston rod 1 at various revolution speeds of the servo motor.

Revolution speed of servo motor (rpm)	Flow rate (mL/min)	Relative combined standard uncertainty (%)
32	0.200	0.04
64	0.403	0.07
112	0.708	0.07
160	1.012	0.07
256	1.623	0.10

Table 2. Flow rates and their relative combined standard uncertainties by piston rod 2 at various revolution speeds of the servo motor.

Revolution speed of servo motor (rpm)	Flow rate (mL/min)	Relative combined standard uncertainty (%)
32	0.200	0.05
64	0.403	0.03
112	0.708	0.07
160	1.013	0.12
256	1.621	0.13

3. Attachment of a transducer and the principle of ultrasonic flow measurement

In this study, the small ultrasonic sensor disk was used for an ultrasonic flowmeter to attach to a measuring pipe. The sensor's resonance frequency of 250 kHz in a radius direction was used for transmitting and receiving sensors. Ultrasonic pulses propagate in both upstream and downstream directions by vibrating ultrasonic sensor in a radius direction. As shown in Figure 2, the ultrasonic pulse is received at R1 or R2 alternately by switching the upstream or downstream side transmitting sensor Tu or Td using a relay. The inside diameter d of the measuring pipe is 0.5 mm.

The received ultrasonic pulse is converted from analog signal to digital signal after signal conditioning and then sampling data are analyzed on a PC.

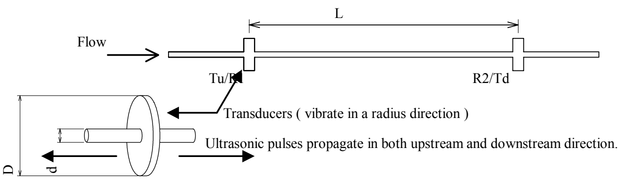

Fig.2. Attachment of a transducer to a measuring pipe

The time-of-flight principle that measures the flow rate from the variation of the transit time of the ultrasonic pulse was used for the ultrasonic flowmeter here. The amplitude of the ultrasonic pulse that transits in a small pipe attenuates very rapidly due to friction of the pipe wall. Therefore, the cross -correlation method was applied to measure the transit time very accurately from weak signals in this study.

First, the ultrasonic pulse is transmitted from the upstream side sensor Tu and received at the downstream side sensor R2. Then, the cross-correlation function $R_{xy}(\tau)$ for two signals, X(t) and Y(t), at sensors T and R is calculated by equation (3).

$$R_{xy}(\tau) = \int_{-\infty}^{\infty} X(t)Y(t+\tau)dt \qquad (3)$$

The transit time τ_u along the flow direction is given by τ at which $R_{xy}(\tau)$ is maximum. Similarly, the transit time τ_d against the flow direction is given. The relation between the transit time and the flow velocity V in the pipe is given by equation (4).

$$V = \frac{L}{2}\left(\frac{1}{\tau_u} - \frac{1}{\tau_d}\right) = \frac{L}{2\tau_u\tau_d}\Delta\tau \quad \left(\Delta\tau = \tau_\delta - \tau_u\right) \qquad (4)$$

Where, L is the length between the upstream and downstream sensors.

There exists a velocity distribution in the pipe which gives rise to the difference between the actually obtained velocity V from the measured transit times by the flowmeter and the mean axial flow velocity Vr in the pipe. The ratio between V and Vr is referred to as the correction factor k. The flow rate Q of the flowmeter is given by equation (5).

$$Q = AkV = \frac{AkL}{2\tau_u\tau_d}\Delta\tau \quad \left(k = \frac{V_r}{V}\right) \qquad (5)$$

Where, A is the cross-sectional area of the pipe.

In this study, characteristics of the developed ultrasonic flowmeter are discussed using k value and Vr is obtained from the reference flow rate of the experimental apparatus.

4. Results and discussions

4-1 Temperature effects on ultrasonic flowmeter

The minimum flow rate of an ultrasonic flowmeter is limited by the effective measurement resolution and the zero flow rate stability. The former can be improved by applying a high measurement resolution of propagation time of an ultrasonic pulse with advanced electronics. However, the latter gives rise to a serious problem for low flow rate measurements and hence it is very important to investigate the cause of zero drift and to develop a method to minimize it.

One of the causes of the zero flow rate instability is the influence of the superposition of the reflected pulses or remaining pulses on the main pulses. The relative angular position among the phase of the main pulses, reflected pulses and remaining pulses should vary with measuring temperature variation and the phase of all the superposed waves depends on the measuring temperature. This problem can be avoided by selecting a suitable sensor material and sensor location. The other cause of the zero flow rate instability is the difference in the thermal characteristics of the two sensors. As described later, the resonance frequency f of a receiving sensor is a function of temperature T and the function f (T) depends on individual sensors. Furthermore, if the resonance frequency of a receiving sensor is not exactly the same as the frequency of an emitted pulse, the sensor detects the pulse at a slightly different frequency, which can cause significant error in very high-resolution measurements. This is shown schematically in Figure 3.

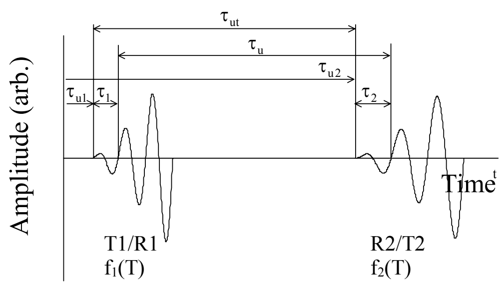

Fig.3.Ultrasonic signals propagated from Tu to R2 along the flow direction

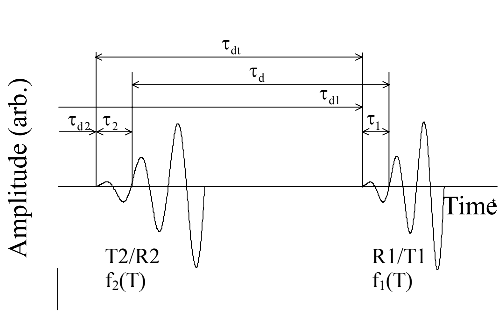

Fig.4.Ultrasonic signals propagated from Td to R1 against the flow direction

If an emitted pulse is detected by two different sensors R1 and R2 at different frequencies f1(T) and f2(T), respectively, as shown in Figure 3, the transit time along the flow direction is given by equation (6).

$$\tau_u = \tau_{u2} - \tau_{u1} + \tau_2 - \tau_1 = \tau_{ut} + \tau_2 - \tau_1 \quad (6)$$

Where, τ_1, τ_2 is the inevitable delay time before the amplitude of the detected pulse increases to a certain level and is given by equation (7).

$$\tau_1 = \frac{n}{f_1(T)} \quad , \quad \tau_2 = \frac{n}{f_2(T)} \quad (7)$$

Where, n is the number of cycles of the pulse wave. Similarly, the transit time against the flow direction shown in Figure 4 is given by equation (8).

$$\tau_d = \tau_{d1} - \tau_{d2} + \tau_1 - \tau_2 = \tau_{dt} + \tau_1 - \tau_2 \quad (8)$$

The information of the flow rate is given from the time difference between equations (6) and (8) as shown by equation (9).

$$\Delta\tau = \tau_{dt} - \tau_{ut} + 2n\left(\frac{1}{f_1(T)} - \frac{1}{f_2(T)}\right) \quad (9)$$

Therefore, the effect of temperature on equation (9) is given by equation (10).

$$\frac{\partial}{\partial T}(\Delta\tau) = \frac{\partial \tau_{dt}}{\partial T} - \frac{\partial \tau_{ut}}{\partial T} + 2n\frac{\partial}{\partial T}\left(\frac{1}{f_1(T)} - \frac{1}{f_2(T)}\right)$$
$$\approx 2n\frac{\partial}{\partial T}\left(\frac{1}{f_1(T)} - \frac{1}{f_2(T)}\right) \quad (10)$$

This equation shows that if temperature characteristics of the resonance frequency of two receiving sensors are not unique, equation (10) is not zero, which suggests that the flow rate including zero flow is affected by temperature changes.

Measurement results of temperature dependency of resonance frequency and quality factor are shown in Table 3. The difference in temperature characteristics of the two sensors shown in Table I is very small. However, equation (10) shows that the difference yields considerable zero drift with only a degree change of temperature, which causes a large error at very low flow rate measurements.

Table 3. Temperature dependency of resonance frequency and quality factor of two ultrasonic transducers A and B

Temperature (℃)	Resonance frequency (kHz)		Quality factor	
	A	B	A	B
10	254.09	248.68	52.55	23.05
25	252.91	247.92	50.73	22.45
40	252.06	247.05	43.75	20.26

It is necessary to find a pair of sensors with very close temperature characteristics, by testing the characteristics of many sensors, for the development of an ultrasonic flowmeter with small zero drift. However, this is impractical and it will be very difficult to ensure long-term reliability.

A new method applying a common receiving sensor with two holes in the disk for passage of a measuring pipe was used for the ultrasonic flowmeter to solve the problem of the difference in characteristics of a pair of sensors in this study. The schematic diagram of the developed ultrasonic flowmeter is shown in Figure 5. The loop length is 500 mm and the length from Tu to R or R to Td is 100 mm. The ultrasonic pulse is detected twice by the common receiving sensor and any change of the resonance frequency characteristic of the receiving sensor has practically no effect.

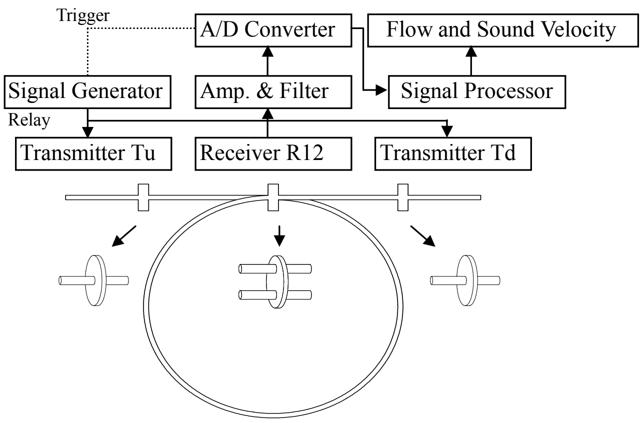

Fig.5. Schematic diagram of a newly designed ultrasonic flowmeter

4-2 Zero point stability and resolutions of ultrasonic signal processing system

The transit times of ultrasonic pulses were measured to examine the zero stability at the zero flow rate and the standard deviation of measurements was evaluated from the zero flow instability. Examples of received signals for the developed ultrasonic flowmeter are shown in Figure 6. The transit time was measured from the first pulse signal X(t) and the second pulse signal Y(t) using both the zero-cross method and the cross-correlation method for comparison. The third pulse signal is a reflected signal from the outlet edge of the measuring pipe.

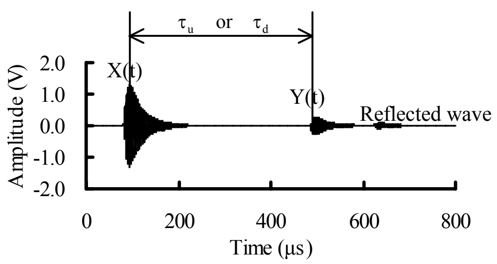

Fig.6.Ultrasonic signals of designed ultrasonic flowmeter

The S/N ratio of detected signals of ultrasonic pluses is very sensitive to the standard deviation of measurements of the developed flowmeter. However, the figure shows that the second ultrasonic pulse is largely attenuated. It is known that scattering of sound propagation occurs when the wavelength is almost equal to the pipe diameter. But the wavelength of the ultrasonic pulse used in this study is about 5 mm which is sufficiently bigger than the measuring pipe diameter of 0.5 mm. Therefore, the propagation mode of the ultrasonic pulse in a liquid should be a plane wave and it is supposed that there is no effect of scattering. Thus, it is thought that the major factor of the attenuation is the friction of the measuring pipe wall. Further study will be necessary to improve the problem.

As for a short-term stability of the measurement, the transit times τ_u and τ_d are not measured simultaneously, but are measured successively. However, measurements are made in a very short time and the effects of any changes in measuring conditions during measurements should be very small. On the other hand, it is very difficult to achieve a good long-term stability. An example of the long-term measurement of the time difference $\Delta\tau$ using the cross-correlation method is shown in Figure 7. The temperature was kept within 22.0 to 22.5 degrees during measurement for 6000 s. It is thought that the variation is caused by the difference in temperature characteristics of the two holes of the sensor.

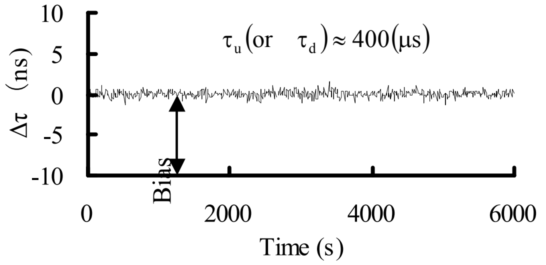

Fig.7.Long term measurements of the time difference

The analogue signal detected by the sensors is converted into the digital signal at sampling frequencies of 12.5, 25, 100 MHz to examine the effect of sampling speed. Measurements of the time difference $\Delta\tau$ at each sampling frequency were repeated 50 times using the zero-cross method and the cross-correlation method. The standard deviation of the measurements using the cross-correlation method is smaller than that using the zero-cross method at all sampling frequencies tested, as shown in Table 4. Therefore, it is thought that the time resolution of the ultrasonic flowmeter can be made smaller even at the low frequency of 12.5 MHz using the cross-correlation method.

Table 4. Standard deviations of the time difference measurement at various sampling frequencies.

Sampling frequency (MHz)	Zero-cross (ns)	Cross-correlation (ns)
100	1.9	0.5
25	2.6	0.7
12.5	3.8	0.8

4-3 Results of very low flow rate measurement using the developed ultrasonic flowmeter

A series of calibrations of the developed ultrasonic flowmeter were carried out in the flow rate range between 0.2 and 1.6 ml/min to examine its repeatability. Results of very low flow rate measurement are shown in Figures 8 and 9. Each point in the figures is the averaged value of 200 measurements. Solid lines in the figures show the predicted scatter limit boundary P that is defined using the standard deviation σ at velocity V by equation (11).

$$P = \frac{V \pm 2D}{V} \qquad \left(D = \sqrt{\frac{\sigma_0^{\ 2}}{n_0} + \frac{\sigma_V^{\ 2}}{n_V}} \right) \tag{11}$$

Where, n is the number of averaging, the suffix 0 denotes zero velocity and the suffix V denotes velocity V.

Measured k values were almost all scattered within the predicted region. A standard deviation of flow rate measurements is about 0.01 ml/min. These results suggest that the developed ultrasonic flowmeter can sufficiently measure low flow rates rendering it useful for industrial applications.

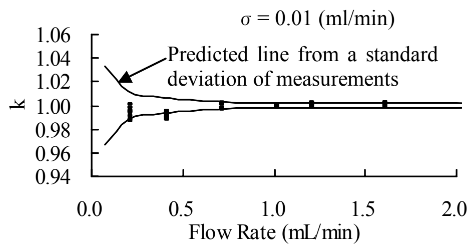

Fig.8.Calibration results at 100 MHz sampling frequency

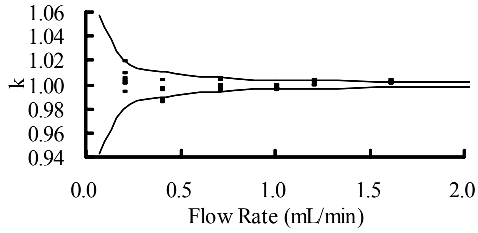

Fig.9.Calibration results at 25 MHz sampling frequency

5. Conclusions

In this study, small disk ultrasonic sensors were used to develop a very small ultrasonic flowmeter with a measuring pipe of less than 1 mm in diameter. The feasibility of an ultrasonic flowmeter to measure a liquid flow rate below 1 ml/min was investigated experimentally. Very low flow rate measurement results of the developed flowmeter were almost all scattered within the range predicted from the standard deviation of measurements. The flowmeter was able to stably measure the flow rate of less than 1 ml/min with the standard deviation of about 0.01 ml/min. This result suggests that it can measure a very low flow rate range rendering it useful for semiconductor industry.

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Reprinted from Trans. of the SICE, Vol.36 No.12, 1071/1078 (2000)