Mass Flow Sensor Using Dual SAW Device

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Abstract The application of SAW devices to a thermometric mass flow rate meter with a reference channel for temperature compensation is presented. The sensor is composed of a delay line device with two channels, namely a reference channel that does not come in contact with the fluid and a sensing channel that makes contact with the fluid. The mass flow rate of gases can be obtained by measuring the temperature change of the device caused by drawing heat from the surface with constant temperature due to the fluid. The results obtained from flow rate measurements of several gases demonstrate that the proposed device is effective as a flow rate meter. Moreover, it is also shown that the response characteristics to mass flow rate changes and the response stability for fluids were improved by taking the phase difference between the signals of the reference channel and the sensing channel as the gas flow rate.

I. INTRODUCTION

Accurate flow rate measurement technology is required in commercial transactions of gases, administration of medical gases, manufacture of products whose raw materials include fluid(s), machinery powered by fluid(s), etc. In addition, due to current environmental issues, there is an ever-increasing need to conserve energy; in order to do this, it is crucial to control flow rates of fluids used as heat sources or motive energy, media and raw materials of heat exchange, etc. In a situation like this, when choosing a flow rate meter, an important question to ask is whether the flow rate to be measured is a mass or volume rate. Thermal mass flow rate meters are generally used to measure flow rates of gases. These meters have several advantages; since they are thermal-based, such meters can measure mass flow rates directly, and since they have no moving parts, they require no maintenance work.

With a thermal mass flow rate meter, a heated object is brought into contact with a flowing fluid, and the amount of heat transferred to the fluid is measured. In other words, it measures temperature changes in an object to directly obtain the mass flow rate. Many kinds of temperature sensors are employed to measure how much heat is transferred. Proposals are being drawn up for a new technology that uses surface acoustic wave (SAW) devices, which are sensitive to temperature changes, as a new temperature sensor [1],[2],[3].

A SAW can be easily excited on a piezoelectric substrate by using an interdigital transducer (IDT). Since a large proportion of the wave's energy is concentrated within a depth of a single wavelength of the substrate's surface, its propagation characteristics are readily affected by external changes, such as those of a physical or electrical nature. There have been many reports of SAW sensors that utilize these changes in the propagation characteristics caused by external factors [4],[5],[6]. Moreover, since SAWs are slower than electromagnetic waves by approximately five orders of magnitude , SAW devices can be made more compact than their electromagnetic counterparts. In addition, high-frequency SAWs enable more precise measurements to be taken and at higher resolution.

This paper discusses an application of SAW devices to a thermal flow rate meter that utilizes the temperature characteristics of SAWs. The flow rate meter discussed here consists of two channels of delay lines on a piezoelectric substrate; one being the sensing channel and the other is the reference channel. While these two delay lines are maintained at a constant temperature, the fluid to be measured is applied to the sensing channel. Heat is then transferred to the fluid, changing the corresponding delay line's temperature, and this change is detected as a change in the SAW's velocity (phase). Based on the results of this experiment, we also considered a mass flow rate meter that employs a specially designed sensor that we prepared for the experiment. We allowed a wide variety of gasses and liquids to come into contact with the SAW propagation surface and measured the change in the wave's velocity in order to obtain the mass flow rates.

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II. Principle of Mass Flow Meter

A. *Thermal mass flow rate meter*

Consider a cross-section of a fixed area that is perpendicular to a flowing fluid. The volume or mass of the fluid flowing through this cross-section per a unit of time is called the flow rate for the unit section.

The thermal mass flow rate meter is a device that directly measures mass flow rates. The principle of such a meter's measurement is to detect the heat transferred to the fluid and obtain the mass flow rate from the temperature difference created by the transfer. Generally, the relationship between the mass flow rate and the heat transferred to a gas is given by: [10]

$$\Delta P = C_p \times \Delta T \times \Delta Q \quad \text{--- (1)}$$

ΔP : Heat transferred to the fluid per unit time

C_p : Isopiestic specific heat of the fluid

ΔT : Increase in the fluid's temperature

ΔQ : Change in the mass flow rate

Thus, according to Eqn. (1), if a fluid's isopiestic specific heat, C_p, is known, we can determine the mass flow rate by obtaining the temperature difference between two measurement points (T_1 and T_2).

Figure 1 shows an overview of a thermal mass flow rate meter. The flow rate is obtained from the temperature difference between T_1 and T_2.

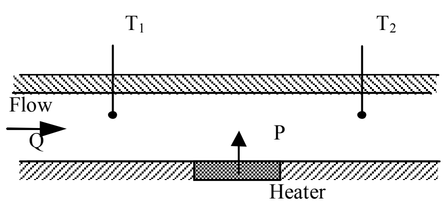

Fig. 1. Outline of thermal mass flow meter

B. *Principle of thermal SAW mass flow rate meters*

Figure 2 shows how thermal measurements of mass flow rates are made using a surface acoustic wave (SAW).

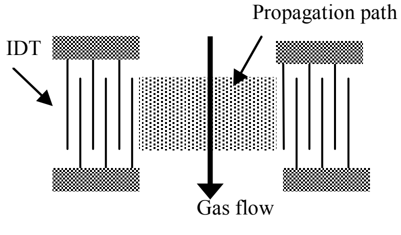

Fig. 2. SAW delay line

To construct a thermal mass flow rate meter using a SAW device, there needs to be some way of detecting slight changes in temperature. In a SAW device, a temperature change also produces a change in the SAW's velocity. This relationship depends on the temperature characteristics of the piezoelectric substrate employed in the device.

Our experiment used a substrate of 128° rot. Y cut X prop. $LiNbO_3$ (128° YX - $LiNbO_3$) has a relatively large temperature coefficient of -74 ppm [9] that provides high sensitivity to small changes in temperature. The SAW device we used as the sensor had delay lines. With a SAW delay line, a change in the SAW's velocity is measured as a change in time, in the form of a phase change. Since the measurement resolution of the propagation delay time depends on the wave's frequency, using a higher frequency can improve both the resolution and the sensitivity. Equation (2) expresses the relationship between a velocity change and a phase shift in a delay line whose propagation path length is l.

$$\theta + \Delta\theta = 2\pi f \cdot l / (v + \Delta v) \quad \text{--- (2)}$$

θ : Phase, l : Propagation path length,

f : Frequency, v : SAW velocity

Thus, we can obtain the flow rate by measuring the change in the phase shift, $\Delta\theta$.

III. Thermal SAW Mass Flow Rate Meter

A. *Flow sensor employing SAW delay line*

A sensor with a single delay line is greatly affected by changes in the ambient temperature. Such interference, however, can be cancelled by employing a reference channel.

In this section, we propose a method for stabilizing phase shift measurement by using a reference channel placed on the piezoelectric substrate for compensating for fluctuations in the ambient temperature.

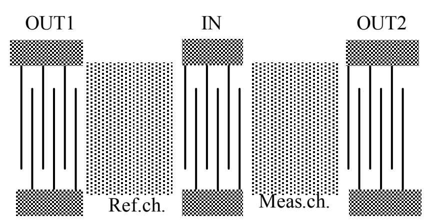

Fig. 3. Outline of SAW device with reference

Figure 3 shows an SAW device featuring two of the same delay lines placed on the same substrate for the purpose of temperature compensation. One of the two delay lines is used as the reference channel (Ref. ch.), while the other is used as the sensing channel (Meas. ch.). The fluid to be measured flows in the sensing channel alone. Then, to measure temperature changes in the sensing channel, we compared the velocity of the SAW propagating in the sensing channel with the velocity of the same wave propagating in the reference channel, which was maintained at a constant temperature.

Each channel of the sensor had a central frequency of 38.2 MHz. There were 10 IDT pairs. The aperture width of the IDT was 20λ (= 2 mm), with λ being the SAW's wavelength. The propagation path length was 2 mm. Also, in order to eliminate external electrical influences, which can interfere with the detection of temperature change, the propagation path surface was electrically short-circuited.

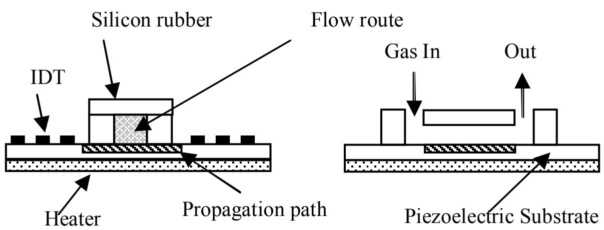

Fig. 4. Cross sectional view of the flow cell

As shown in Fig.4, we placed a flow cell upon the sensing channel to let the fluid come into contact with the delay line. The gas flow route had a square cross-section of 1 mm x 1 mm and ran parallel to the IDTs.

B. Characteristics of the SAW flow sensor

Using the measurement system shown in Fig.5, we obtained the relationship between changes in the SAW velocity in each of the delay line channels and the mass flow rate.

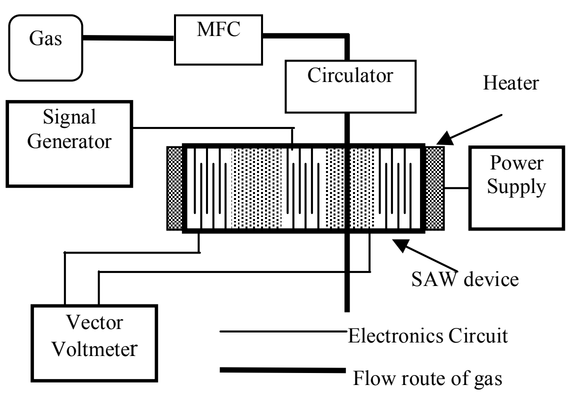

Fig. 5. Outline of gas flow system with reference

The sample fluid's flow route was kept within a constant-temperature bath to keep the fluid at a constant temperature. The constant-temperature gas was fed onto the SAW propagation path of the sensor's sensing channel. We maintained the sensor at a constant temperature by applying constant heat to it from a heater located on the backside of the substrate. Every time the flow rate of the gas changed in the sensing channel, the heat loss of the propagation path also changed, causing the element's temperature to change as well. These temperature changes resulted in a change in velocity between the sensing and reference channels, which we measured in the form of a phase shift using a vector voltmeter. In the experiments, a continuous wave was used to excite the SAW applied to the sensor.

Figure 6 shows the response characteristics in the phase-shift changes observed after the gas was introduced. At time 0 (s) in the figure, the gas flow rate was changed from 0 sccm to 300 sccm. The horizontal axis in the figure indicates the time elapsed. The figure shows the measurement results of the phase shift from the reference channel as well as the phase shift between the input signal and the output wave off the sensing channel. As the results show, using the reference channel brought about a constant state soonest, in which no drift was observed in the phase shift with the elapse of time.

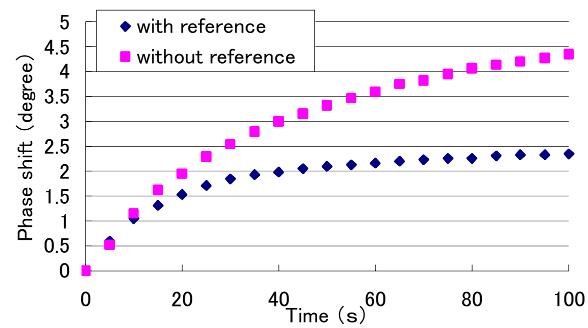

Fig. 6. Phase shift versus Time after it begins to throw gas

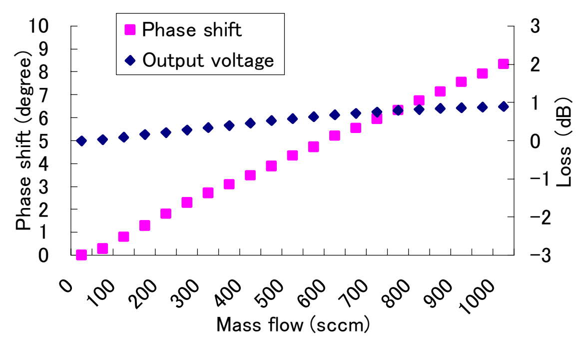

Fig. 7. Phase shift versus mass flow rate of dry air and insertion loss

Figure 7 shows the measurement results for changes in the phae shift as well as for changes in the insertion loss (propagation loss) on the flow rate measurement channel in response to a changing flow rate, in which dry air was used as the fluid.

We changed the flow rate in increments of 50 sccm, from 0 to 1000 sccm and waited for 2 mins after each change for the state to stabilize before measuring each value. As the chart shows, the insertion loss was stable, changing within the width of 1.0 dB, while the phase-shift changes were proportional to the flow rate.

Next, we show the changes caused by fluctuating (increasing and decreasing) cycles in the mass flow rate. Figure 8 shows the measurements of the phase shift from the input signal and Fig.9 shows those of the phase shift from the reference signal.

These two sets of results demonstrate that when the reference signal was used the measurement results depended solely on the flow rate, irrespective of whether the rate was increasing or decreasing.

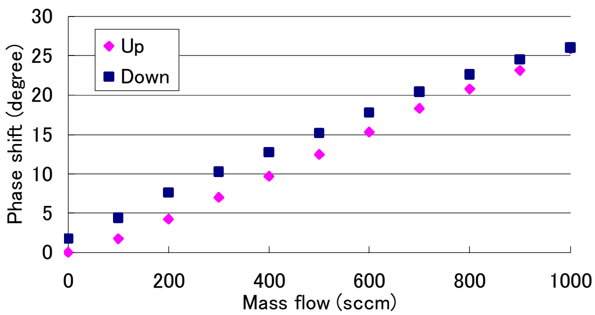

Fig. 8. Phase shift versus mass flow rate

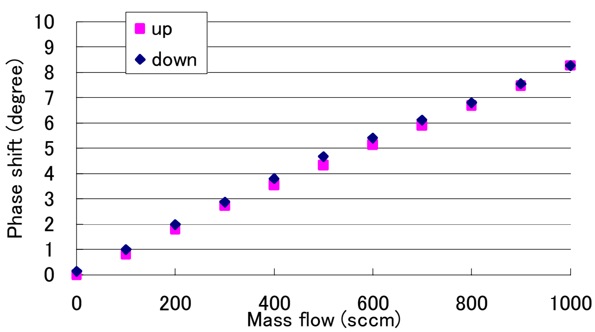

Fig. 9. Phase shift versus mass flow rate using reference

As described above, a reference channel for temperature compensation used in conjunction with a SAW delay line sensor improves the response characteristics and phase characteristics induced by changes in the flow rate.

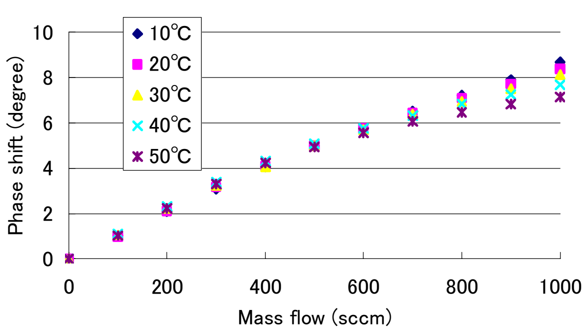

Fig. 10. Phase shift versus mass flow by temperature of circulator

C. Dependence to temperature

Using the measurement system illustrated in Fig.5, we investigated the temperature characteristics of the SAW flow sensor.

Figure 10 shows the relationship between the flow rate and the phase shift as we varied the fluid's temperature by changing the temperature of a constant-temperature bath from 10 to 20, 30, 40, and 50 °C.

In Fig.10, we see that the phase-shift change decreases as the flow rate increases and as the temperature of the gas increases. We believe that this is because some of the heat supplied by the heater to the sensor transfers to the fluid, creating a phase shift; thus, as the fluid's temperature increases, it absorbs less heat, resulting in a smaller phase shift.

Also, at a higher flow rate, the fluid absorbs more heat making the phase shift larger. Depending on the fluid's temperature, however, the heat absorbed by the fluid varies considerably, resulting in different changes in the phase shift; we thus see that the lower the temperature of the gas, the larger the range of fluid rates that can be measured.

Next, we recorded measurements while varying the heater's emission of heat. In Fig.11, we set the power of the heater to 2.23 W, and in Fig.12 to 3.98 W, keeping the constant-temperature bath's temperature at 20 °C and 40 °C.

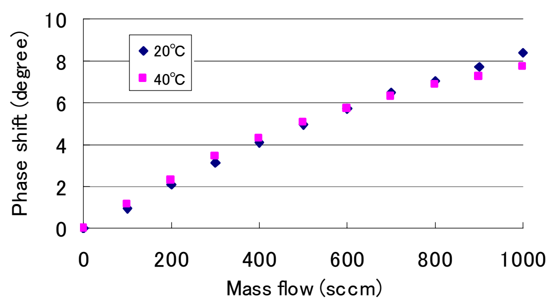

Fig. 11. Phase shift versus mass flow

Heater power = 2.23 W

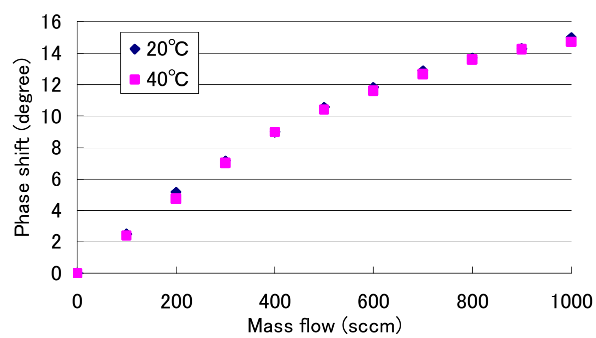

Fig. 12. Phase shift versus mass flow.

Heater power = 3.98 W

Figure 11 shows that at a high flow rate, the phase shift varies when the fluid's temperature changes. Meanwhile, Fig.12, in which the heater releases more heat, shows that the phase shift does not change in response to the fluid's temperature change. This indicates that, within the measured range of flow rates, the heat supplied by the heater was not affected by the fluid's temperature. Thus, by supplying sufficient heat to the sensor, we can expand the range of flow rates that can be measured without affecting the fluid's temperature.

D. Application

Using the system mentioned above, we measured the mass flow rates of argon, oxygen, dry air, nitrogen, and helium. Figure 13 shows the phase shifts that correspond to different flow rates of the respective gases. Each output has a different slope that depends on the specific heat of fluid, demonstrating its dependence on the specific heat. Table 1 shows the relationship between the flow rate of each gas and the change in the SAW velocity as measured in our experiment, as well as the isopiestic specific heat (C_p) and the heat conductivity (λ) of each gas we measured.

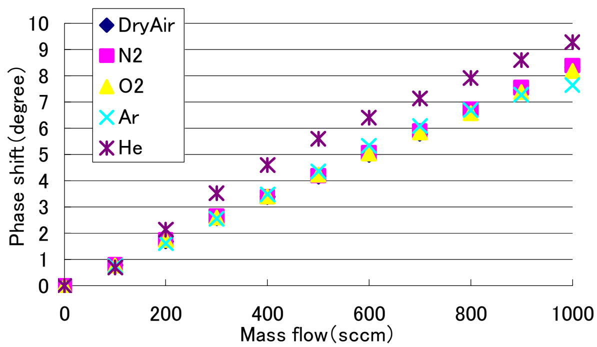

Fig. 13. Phase shift versus mass flow rate

Table 1 Physical parameters of test gases (20℃) [6]
and Linear approximation of Fig. 13.

Gas	C_p (10^3 J/Kg K)	λ (10^{-2}W/m K)	Linear approximation
Ar	0.523	1.62	y = 0.0080x
O_2	0.909	2.44	y = 0.0082x
Dry air	0.992	2.41	y = 0.0083x
N_2	1.038	2.43	y = 0.0084x
He	5.238	14.15	y = 0.0095x

With helium, the measured phase shifts were greater than those obtained with the other gases. We believe this is because its heat conductivity was 6 to 9 times greater than those of the other gases and, therefore, more heat was transferred at the same mass flow rate. These results show that all the measured gases had a linear relationship.

IV. SYSTEM OF FLOW RATE SENSOR

We used a vector voltmeter to measure the basic characteristics of the flow sensor. Such a meter, however, is too expensive to be used in practical applications. Here, therefore, we propose a more practical system that measures phase shifts.

Figure 14 shows the new flow sensor system. The flow of the gas, the SAW excitation by the signal generator, and the heat supply from the heater are the same as those for the system discussed in Section 4.2. In a practical system, instead of the vector voltmeter, a mixer (DBM) mixes the reference and sensing signals to convert the phase-shift signal output into a voltage. The output voltage is then amplified by an amplifier (OP Amp) and measured using a digital multimeter (DMM).

Figure 15 shows the relationship between the changes in the mass flow rate of dry air and the phase shift. We conducted this experiment with the signal generator's frequency set at 37.8 MHz, the constant-temperature bath at 20°C, and the heater's power at 2.23 W. Figure 15 demonstrates that the more practical system that employs a digital multimeter is able to determine the relationship between the flow rate and the output in a similar way to the phase-shift measurement system.

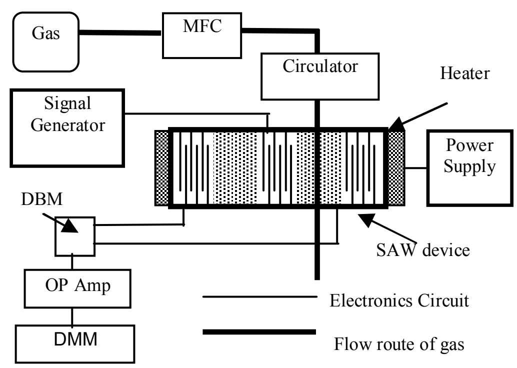

Fig. 14. Outline of gas flow system measured by voltage

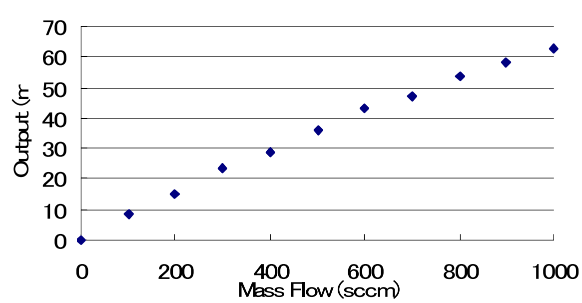

Fig. 15. Output voltage versus mass flow rate

V. APPLICATION OF THE SAW FLOW SENSOR

Figure 16 shows the phase shifts when we changed the flow rate gradually, while Fig. 17 shows the phase-shift change that occurred in a single second with the same gradual change in the flow rate.

We conducted this measurement with the frequency set at 37.8 MHz, the constant-temperature bath at 20°C, and the heater's power at 2.23 W. In this condition the flow rate was changed in the following manner: 0 → 100 → 0 → 200 → 0 → 500 → 1000 → 500 → 200 → 700 → 1000 → 100 → 0 sccm.

In addition, Fig. 18 shows the differences in the phase-shift change at the moment when the flow rate was changed (Fig. 17).

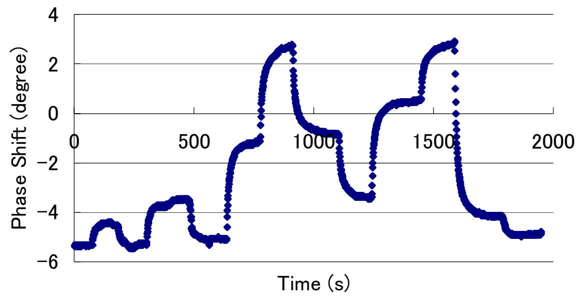

Fig. 16. Phase shift versus flowing quantity change

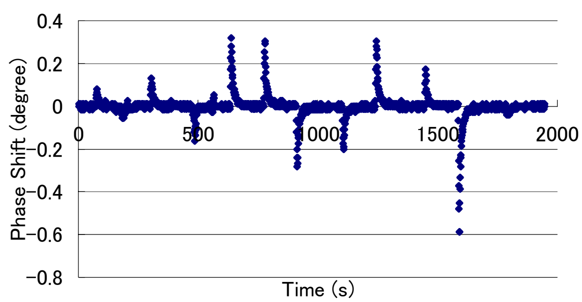

Fig. 17. 5-moving average of phase shift change when mass flow changes

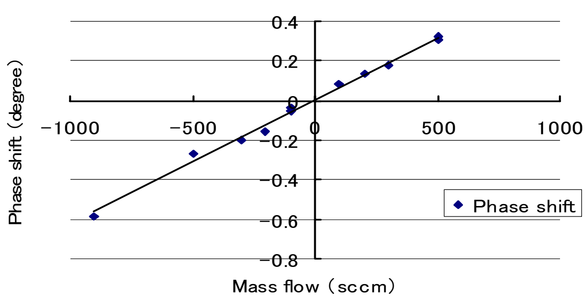

Fig. 18. Phase shift change versus mass flow change

In Fig. 18, it is found that, at the moment when the flow rate changed, the phase shift changed and that the magnitude of this change corresponded to the change in the flow rate. We consider that, as the current velocity, or the speed of the flow, changed, the phase shift changed in response to this changed velocity. The result shows that the SAW flow sensor can be used in a current meter.

VI. CONCLUSION

In this paper, we proposed a new thermal mass flow sensor consisting of two SAW delay lines on a piezoelectric substrate and investigated its characteristics in experiments. It was found that:

1) Use of the reference channel was effective in improving the precision and stability of flow rate measurements.

2) Increasing the heat supplied to the sensor from the heater enabled a broader range of measurements to be recorded.

3) In the experiments using helium and four other gases, there was a linear relationship between the flow rate and the phase-shift output.

Next, to make our sensor more practical, we proposed a detection system featuring a mixer. This system also produced phase output with a linear relationship to the mass flow rate.

Finally, as an application of the SAW sensor, the relationship between changing flow speed and the phase-shift was measured. It was realized that the phase-shift change corresponding to a change in the flow rate. This shows that the sensor is applicable to a current meter as well.

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