MEMS Thermal Time-of-Flight Flow Meter

Yahong Yao, ChihChang Chen, Xiaozhong Wu and Liji Huang
Siargo Ltd., 2041 Mission College Boulevard, Suite 250, Santa Clara, CA 95054 USA
Tel:1-408-969-0368, E-mail:Liji@Siargo.com

Abstract: Thermal time-of-flight (TOF) technology has been considered to be one of the most effective approaches that could provide an accurate flow measurement at ultra low flow speed. While the technology remains on paper for over half a century without real implementation, the lack of market drive may be one of the major reasons. Current demands in energy management such as city natural gas metering, medical applications for respiratory machines and others have revitalized this technology. Thermal TOF technology in principle can provide accurate flow speed measurements for gases regardless of its gas compositions. However, traditional design of TOF sensors is often very vulnerable to fluidic conditions, in particular, moisture, particles and other contaminations. In this paper, we present a thermal TOF gas flow meter that is equipped with a robust MEMS thermal TOF sensor which can be used in fluid where moisture and particles exist. The design and fabrication of the MEMS TOF sensor are described followed by its circuit scheme. The design of the flow meter and the test results are presented.

Keywords: MEMS flow meter, Time-of-flight, thermal flow sensor

1. Introduction

The thermal flow sensing technologies can be classified into three categories in terms of the working principle:[1] (a) anemometric, (b) calorimetric, and (c) time-of-fight (TOF). The former two directly or indirectly measures the amount of heat that has been carried away by the flow media. The amount of the heat carries away is directly proportional to the flow speed as well as the mass of the fluid and hence these two technologies provide the direct mass flow measurement. For TOF flow sensing technology, however, it measures the time span for heat wave carried by the fluid to travel from the heater position to the downstream sensing element position. The lower the flow speed is, the longer time it takes for the heat wave to travel which enables a better signal process capability. This character is then completed different from the other two thermal flow sensing technologies, which suggest that TOF would be superior for low flow range and can be used in combination with the other two technologies so that the dynamic range of the entire flow can be addressed. This combination would particular useful as the TOF can provide composition independent measurement while the other two can provide the direct mass flow information. In addition, TOF approach could be an ideal one to apply for applications where the fluidic composition varies during measurement, such as city water gas metering and human respiratory equipment.

For traditional TOF sensor design, the heater and sensing element are made of two metal wires with platinum as the materials in most cases.[2,3] The wires are installed in the middle way of the flow path. During flow measurement, both heater and sensing element are having electric current passed through. Such a configuration is very vulnerable to humidity as the moisture could cause the change of the thermal conductivity of the medium leading to the variation of thermal response and substantial performance alteration. Particles with high flow speed could damage the wires and cause failure of operation. In recent years, TOF sensors made by MEMS technology have been discussed. For the TOF MEMS flow sensor design, both heater and sensing element are disposed on a heat-isolated membrane.[3-5] The sensor can be installed with its surface in parallel with the flow direction in designated flow channel such that it would be less vulnerable to particle impact. Furthermore, the surface of the elements can be passivated with an electrically isolative but thermal conductive layer which makes the sensor better withstand against humidity.

There are two approaches to excite the heater and record the heat wave flight time. The first methodology is to apply an electric pulse to the heater[2, 4] and the fluid passing the heater will carry the heat to the downstream sensing element. This technique has the merit of a simpler circuitry, but the disadvantage is that for small flow speed, the pulse signal detected by the sensing element could be very blurred [4] and the exact travel time is hard to be determined, therefore the accuracy could be questionable. The second approach is to use a single frequency electric signal to drive the heater and the sine wave heat profile is detected by the sensing element.[3,5] The phase shift between the sensing element and heater is equivalent to the flight time of the heat wave and is correlated to the flow speed of the fluid. Since this approach is dealing solely with the phase shift element of the signal, the uncertainties of signal amplitude will not alter the results. Another advantage of the approach is that since it is using single frequency throughout the entire circuitry, the demodulation technology that is similar with the high-precision lock-in amplification technology can be employed thus to provide the feature of high immunization to noise. In addition, all issues that are plaguing DC excitation have been eliminated in this single frequency approach such as 1/f noise, DC drifts of electronics and line noise pick-up.

This paper describes the design and fabrication of the MEMS TOF sensing chip as well as the electronic circuit scheme. The sensing chips are further assembled into flow meters and the test results are presented.

2. MEMS TOF Sensing Chip Design and Fabrication

2.1 MEMS TOF Sensor Design

A TOF sensor can have one heater and one sensing element only. To enhance the measurement accuracy, three elements with different spaces in between have been designed on the membrane for the present design. Any two of the three elements can be configured as a TOF sensor. If the center element is used as the heater and one of the rests as the sensing element, then the chip has the bidirectional measurement capability. In the design shown in Figure 1, the spaces between the adjacent two elements are 250µm and 200µm center to center, respectively. Each element is designed as inter-digitized patterns considering the thermal field distribution and the space taken.

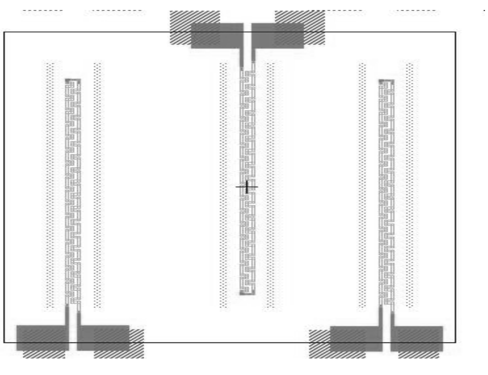


Fig. 1 Top view of the mask design of the TOF MEMS sensor chip.

2.2 TOF Sensor Fabrication

The TOF sensors were fabricated with the silicon micromachining technology. The process started with a single crystal silicon wafer. The suspending silicon nitride membrane was made by low pressure chemical vapor deposition. Then the heater and sensing elements were deposited on top of the silicon nitride membrane. The elements were passivated with another layer of silicon nitride. The contact openings of bonding pads and the open slots on membrane were etched by plasma etcher subsequently. Finally, the bulk silicon was etched away from the wafer backside leaving the front layers to form the heat-isolated membrane structure. The cross-sectional view of the sensor is shown in Figure 2.

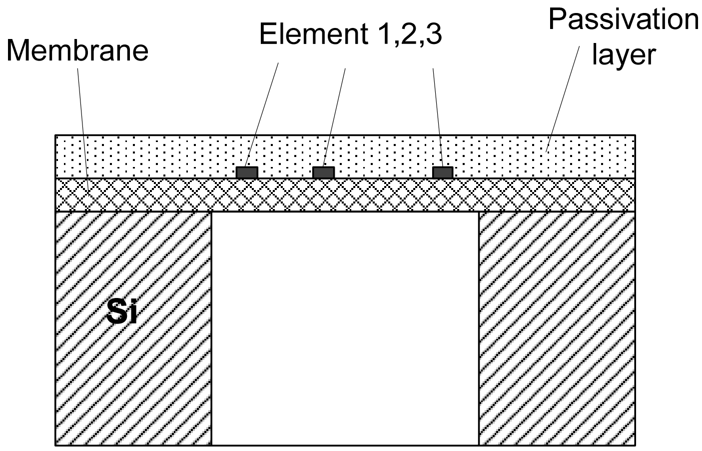


Fig. 2 The cross-sectional view of the TOF sensor

3. Circuit Topology

The single frequency drive approach is taken in the circuit design due to many of its performance advantages. The functionality circuit contains four basic building blocks: (a) heater-driving generator; (b) sensing signal conditioning, (c) pre-phase-lag detector, and (d) μ-controller. The detailed description of every block is as the following.

(a) Heater-driving generator: This block is basically an oscillator generator. It generates a perfect sine signal at the correct frequency. It would be able to provide both a sine and cosine signal for the phase-lag detector block. It also contains a unit to provide proper amplitude to excite the heater.

(b) Sensing signal conditioning: It records the sensing signal and provides proper amplification.

(c) Pre-phase-lag detector: This block provides the capability of detecting the phase lag between the sensing signal and the heater signal. This function can be accomplished by either software or hardware approaches. The former approach needs to acquire a large amount of data and powerful computing, which is not practical for a meter product. Hence the phase-lag detection is performed by electronic components. It uses modulators to detect the in-phase and out-phase voltages over the heater driving signal.

(d) μ-controller: It takes the in-phase and the out-phase voltages and calculates the phase-lag signal. Also μ-controller takes meter-related management work such as display and communication.

The functionality circuit block-diagram is as Figure 3.

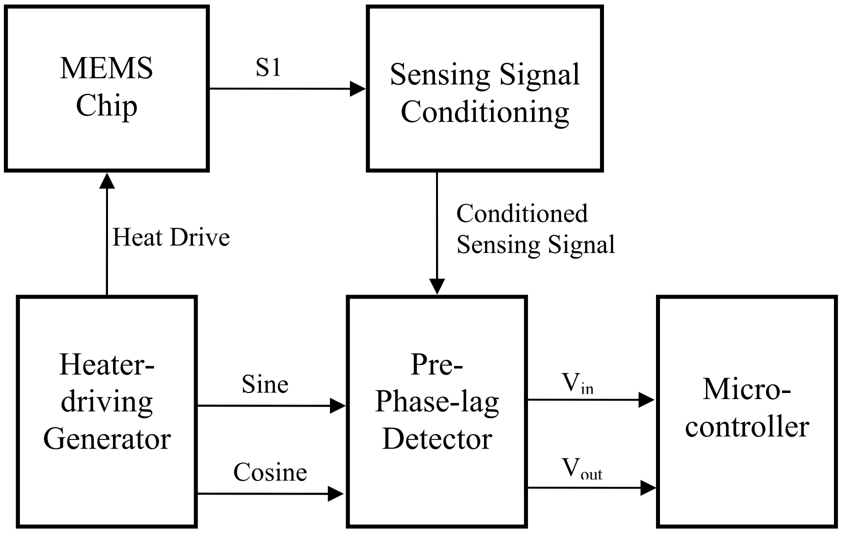


Fig. 3 The functionality block diagram of the TOF circuit.

4. The TOF Meter Test Results

4.1 Sensor Packaging and Testing Setup

Before package the sensor with the meter head, the sensor was tested for its functionality in the test bench as shown in Figure 4. The MEMS TOF chip was bonded onto a carrier. The carrier was further connected with a feed-through that was then installed into a one-inch (diameter) pre-manufactured stainless steel flow meter body in which the flow channel was made with a venturi structure for flow stability as seen in the figure. The sensing element on the sensor was placed such that it was located at the center of the channel while the surface of the sensor was in parallel with the flow direction. The sensor was then tested with the circuit described in Section 3.

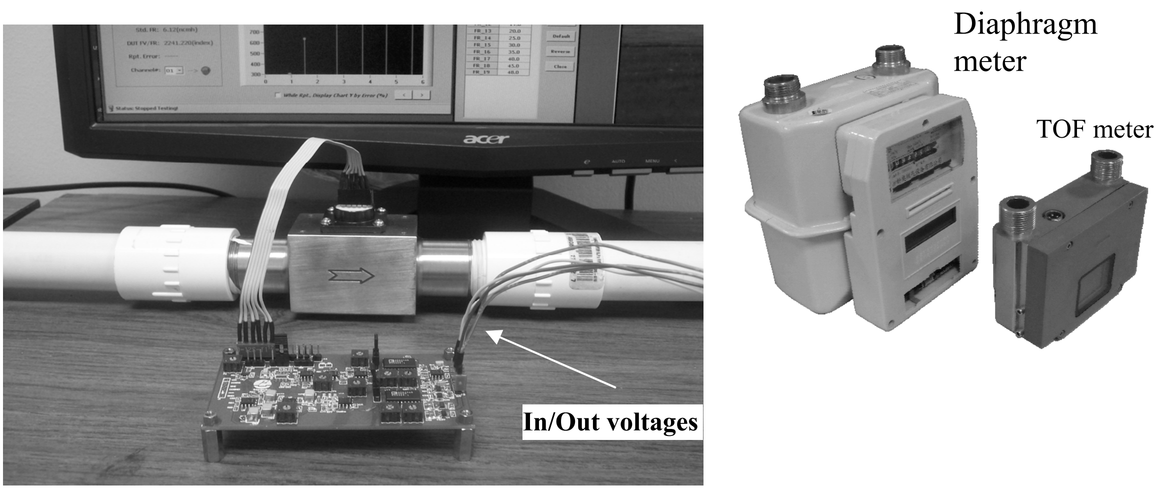


Fig. 4 The testing setup and assembled meter compared with diaphragm meter

One of the purposes for the present work is to test the TOF meter for residential natural gas applications, as the current diaphragm meters do not have the capability for temperature and pressure compensation. In addition, data transmission on the diaphragm meter platform is very costly and often erroneous. Further, the natural gas composition is usually not a constant from place to place if the sources are deviated. The designed TOF meter is exhibited in Figure 4 and for comparison a traditional diaphragm meter is also shown in the same figure.

4.2 The Excitation and Sensor Response

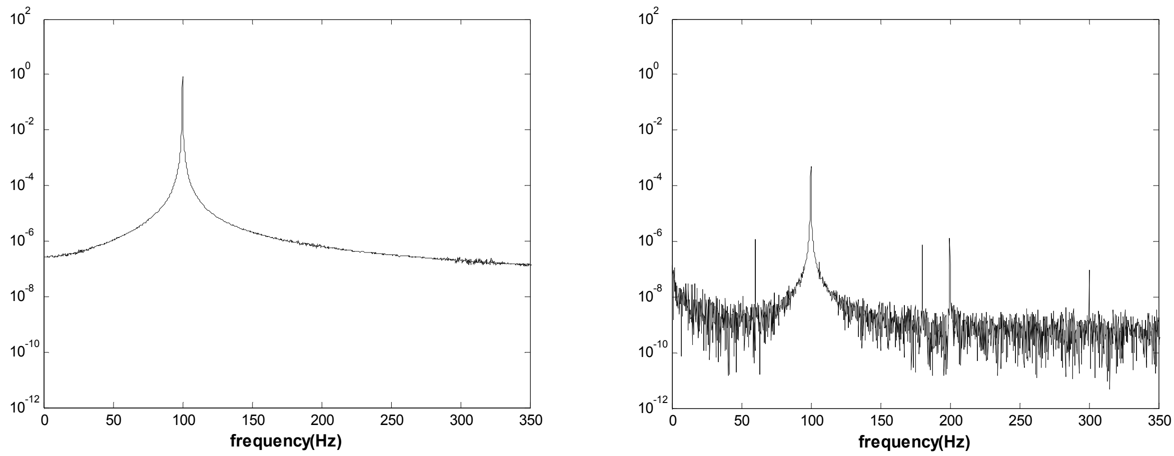


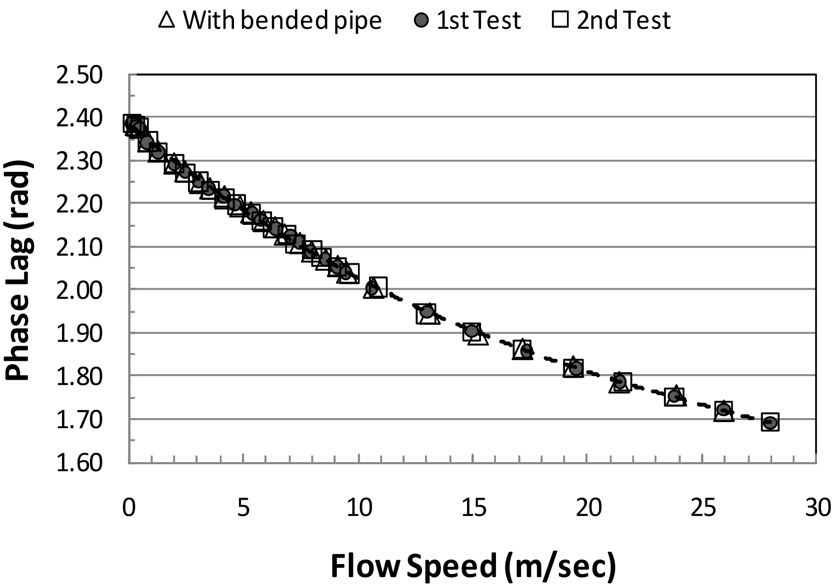
Fig. 5 The frequency spectra for (a) excitation and (b) sensor signal.

Before the meter performance test, it is helpful to look into the key signals among the circuitry. In the circuit described in Section 3, the heater-driving generator block is very critical because it is the original AC signal to be used throughout the entire circuit. A clean, single frequency sine wave is required to drive the heater, and the sine wave is further sent into the pre-phase-lag detector block where it modulates the sensing signal. To evaluate the quality of the sine wave generated, its frequency spectrum is plotted in Figure 5(a). The frequency spectrum of the induced sensing signal is plotted in Figure 5(b). One can see from Figure 5, the generated driving signal is a very clean single frequency wave at 100Hz, while the sensing signal has a very prominent peak at 100Hz as well. It also contains the harmonic frequency of 200Hz and 300Hz of the driving signal but with much lower amplitudes. The city electric frequency of 60Hz and its harmonics also mix into the sensing signal. The harmonics of the driving frequency can be filtered with a low pass filter before sending into the pre-phase-lag detector. The 60Hz and its harmonics will be totally suppressed with the highly selective demodulation technique that is very similar with the well-known precision lock-in amplification technology. The entire circuitry approach ensures a high immunization to noises, drift, etc. This lays a strong foundation to the excellent meter reproducibility to be discussed in the following section.

4.3 Dynamic Range and Reproducibility

As we have discussed above, one of the excellent applications for the TOF flow sensing technology would be for the city gas custody transfer deployment. In the city gas applications, the dynamic range and reproducibility are two important properties. The existing diaphragm meters have a 160:1 turndown and excellent reproducibility. Therefore such performance should be matched if the all electronic gas metering technology would be widely implemented. Figure 6 shows the measured phase-lag data for the meter with the MEMS TOF sensor in the flow speed of 0.15 to 30m/sec dynamic range. During the tests, a laminar flow block with uncertainties of ±0.2% was used for reference of all data collection. The meter had a 1" venture flow channel and a flow conditioner at the flow entrance in the meter. For flow in a pipeline of 1" diameter, such flow speeds correspond to the flow rate of approximately 4.5 to 910L/min (0.3 to 55m^3/hr). This almost 200:1 turndown and large flow capability would cover the most of applications in industrial utility custody transfer. The data show that the phase-lag is inversely related to the flow speed, i.e. when flow speed increases, the phase-lag between sensing element and heater becomes smaller because it takes less time for the heat wave to travel from heater position to sensing element position. Similar experiments were performed for the dynamic flow range of 0.01 to 3.0m/sec (0.025 to 4m^3/hr). This range covers the applications for residential gas custody transfer. The measurement data were very much similar in character. Additional tests were performed with bended pipeline as shown in Figure 6. The data obtained indicated that 90º bended pipeline would not affect the performance of the meter.

For the reproducibility tests, the same measurements were performed more than 20 times to demonstrate the performance. Two of the curves are displayed in Figure 6. It can be observed from the figure that the differences among the data points are hardly distinguished. The calculation from the data indicated that the maximum deviations (errors) among the 20 times measurements were within 0.1% at the full dynamic flow speed range. This characteristic is far better than those for calorimetric or anemometric approach where the reproducibility at low flow would always be a problem resulting in a full scale accuracy that could not meet the requirements of custody transfer in applications such as city gas metering.



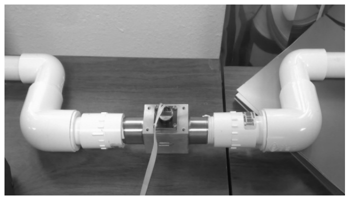


Fig. 6 Phase-lag v.s. air flow speed. Test configuration with bended pipe is also exhibited.

4.4 TOF Flow Meter for Liquid

As discussed above, the excellent reproducibility in low flow speed measurement for the TOF sensor was outstanding against the other technologies. The capability for flow measurement of fluid at low flow would be very useful for current medical applications such as the dose control in homecare that has increasing demands for new technology. In the medical injection or medical infusion pump prescription, the "self-service" approach requires more automation compared to those practices in hospital. To this end, the data for medical fluid flow would be a necessary requirement. Although theoretically the information could be alternatively obtained from the measurement of the pressure, but when the flow speed is very slow as it is usually the case such as the injection, direct measurement of the fluid flow rate would be critical. In our present study, we use the same TOF sensor discussed above to investigate the possibility of the applications in medical fluid flow rate measurement. The TOF sensor was assembled into a plastic package as shown in Figure 7. The flow channel cross-section inside the package was 1.0mm×1.5mm and the TOF sensor surface was placed at the flow channel wall. Distilled water was then applied to the meter with the flow dynamic speed from 1.9 to 62mm/sec corresponding to flow rate of 10 to 330mL/hr. The data shown in Figure 7 indicated that the sensor can well be applied for such applications.

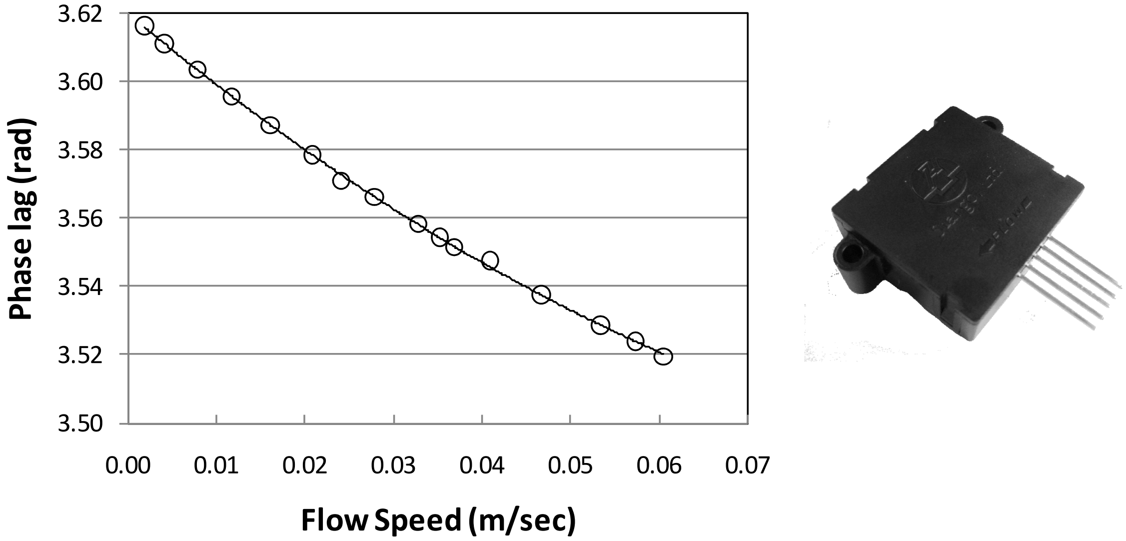


Fig. 7 TOF meter for liquid flow applications

5. Concluding Remarks

This paper presented the design, fabrication of a MEMS TOF sensor chip, the circuit topology for the flow meter with such a sensing chip, as well as the experimental test data for the TOF flow meter. The data indicated that the technology could provide excellent reproducibility with unprecedented stability towards the very low flow speed regime as compared to the current thermal mass flow products on market. Such results could also come from the data logging approach of phase-lag detection instead of the measurement of signal amplitude which is known to have large fluctuation particularly at low flow speed domain in other thermal flow sensing technology.

The application of the same TOF flow sensor for liquid flow showed that the sensor could be used for ultralow flow applications and could be very effective for today's medical innovations.

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