FLUIDIC SHEAR-STRESS MEASUREMENT USING SURFACE-MICROMACHINED SENSORS

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Abstract **- A poly-silicon hot-film shear-stress sensor insulated by a vacuum-chamber underneath has been designed and fabricated by the surface micromachining technology. The sensor is operated at both constant current and constant temperature modes. The dynamic performance (including time constant and cut-off frequency) measurement, calibration, and temperature compensation of the sensor have been realized.**

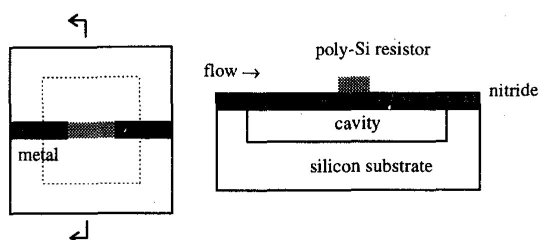
I. INTRODUCTION

Fluid flow over a solid wall generates a velocity gradient that produces shear stress at the wall. This wall shear stress is one of the important flow properties in aerospace engineering and fluid mechanics[1]. Presently, there are many measurement techniques for shear stress [1]. However, none of them can simultaneously satisfy the operational requirements for turbulent boundary layer research: fine spatial resolution (~100μm), fast frequency response (>5kHz), and high sensitivity. With the help of micro-machining technology, the floating-element shear stress sensor has satisfied the requirement of spatial resolution[2-3]. But the other requirements remain to be a problem.

Flush-mount hot-film anemometers are commonly used to measure wall shear stresses. The method of measurement is based on a simple heat transfer theory. The drawback of traditional hot-film anemometers is heat transfer to the substrate which results in low sensitivity. An new micromachined hot-film shear-stress sensor insulated by a vacuum-chamber underneath has been proposed and designed in the present study [6] for a distributed micro-electro-mechanical system (MEMS), which has high sensitivity and can achieve all the above requirements. The theory, circuit design, and more extensive experimental results of the sensor will be given in this paper.

II. DESIGN AND FABRICATION

Fig. 1 schematically shows the top and cross-sectional views of the micro hot-film sensor. By using micromachining technology, a vacuum chamber (cavity), the square part (dashed line) in Fig. 1, is placed under a thin silicon nitride film. The typical size of the cavity is 200x200x2 μm^3. A poly-silicon strip (80-200 μm long, 2 μm wide, and 0.45 μm thick) is deposited on the silicon nitride film and functions as the sensor element. Metal leads connect the sensor element to the outside through bonding pads. The flow direction is perpendicular to the length of the sensor strip.



(a)

Fig. 1 Schematic top (a) and cross-sectional (b) views of the shear stress sensor.

The cavity is formed by sacrificial-layer (PSG, phospho-silicate glass) technique. Both silicon nitride and poly-silicon layers are deposited by LPCVD (low pressure chemical vapor deposition). The poly-silicon resistor is uniformly doped to a low sheet-resistance of typically 50 Ω/•. The measured TCR (temperature coefficient of resistivity) of the sensor at this doping level is about 0.09%/°C. Typical resistance of the sensors is 2-5 kΩ. The detailed process steps are given in [5-6]. A SEM picture of the micro-fabricated sensors is shown in Fig. 2.

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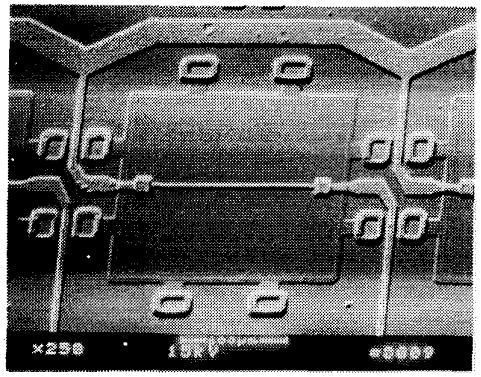


Fig. 2 A SEM picture of the micro sensor.

III. THEORY AND CIRCUITS

Hot-film anemometer utilizes the convective heat transfer from the heated sensor to the above fluid to measure the shear stress generated by the fluid. The resistance of the sensing element R can be approximately related to its temperature T by a linear equation

$$R=R_o[1+\alpha(T-T_o)] \quad (1)$$

where R_o and T_o are the average resistance and temperature at a reference condition which is usually the ambient condition, and α is the TCR (temperature coefficient of resistivity) of the sensor. An important parameter governing the operation of hot-film sensor is the overheat ratio defined as [8]

$$\alpha_T=(T-T_o)/T_o \quad (2)$$

where T is the temperature of the heated sensor. In operation, it is more practical to use a resistive overheat ratio defined by

$$\alpha_R=(R-R_o)/R_o \quad (3)$$

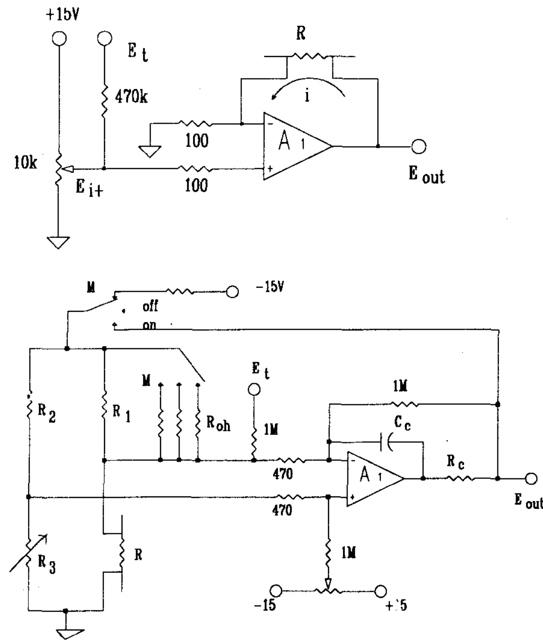
where R is the resistance of the heated sensor. The relationship between the two overheat ratios is $\alpha_R= \alpha T_o\alpha_T$.

The heating power of a hot-film sensor operating in steady state can be correlated with wall shear stress τ_w as follows[1]

$$i^2R=(T-T_f)(A+B\tau_w^{1/3}) \quad (4)$$

where T_f is the temperature of the measured fluid, i is the heating current going through the sensor, A and B are calibration constants. The equation shows that the heating power is linearly proportional to the one third power of the shear stress.

The usual operation mode for hot film sensor is either constant current (CC) or constant temperature (CT). Since the resistance of a micromachined hot-film sensor (>1kΩ) is generally higher than a traditional one (~50Ω), traditional anemometer circuits need to be modified for present case. Figs. 3 (a) and (b) show the modified circuits for CC and CT operations, respectively, in which R represents the sensor and E_{out} is the output terminal. In Fig. 3 (b), R_{oh} is used to adjust resistive overheat ratio, R_c and C_c are for compensation. Fig. 3 (a) is basically a voltage controlled current source and it can provide constant current to the sensor with resistance up to dozens of kilo-ohm.



(a)

(b)

Fig. 3 The CC(constant current) (a) and CT(constant temperature) (b) circuits of the sensor.

IV. MEASUREMENTS

1. Dynamic Performance

Since suitable velocity fluctuations are not readily available, electronic test signals are usually used to determined the time constant of the sensor. According to both theoretical analyses[9] and experimental confirmation[7], the frequency response or time constant can be obtained by feeding either an electronic sine wave or a square wave into an anemometer circuit. The terminal E_t in Fig. 3 is for this purpose.

The measured time constant and cut-off frequency of the micro sensor at CC mode are typically 300 μs and 500 Hz, respectively. By using feedback at CT mode, much better dynamic performance can be obtained. The measured time constant and cut-off frequency at CT mode are typically 72 μs and 11 kHz, respectively. A higher frequency response can be obtained by changing the overheat ratio of the sensor. Fig. 4 is a typical measured curve describing the cut-off frequency change vs. the resistive overheat ratio and it can be seen that a cut-off frequency of 70 kHz at CT mode can be reached.

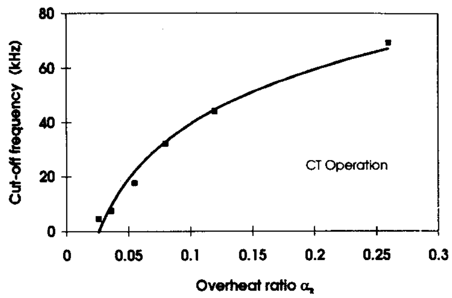


Fig. 4 The cut-off frequency of the micro sensor vs. resistive overheat ratio at constant temperature mode.

2. Shear Stress Calibration

In order to correlate the output voltage with wall shear stress(τ_w), two calibration methods are usually used. In the first method, τ_w in a fully developed channel flow is related to the streamwise pressure gradient by[1, 10]

$$\tau_w = -0.5h(dP_x/dx) \quad (5)$$

where P_x is the local pressure, x is the stream-wise coordinate, and h is the height of the wind tunnel. In the second method, an empirical relationship between the free stream velocity and shear stress is used[5-6]. Here the first method is used.

The micro shear stress sensor is flush-mounted on the wall in the fully developed region of a wind tunnel. The calibration results for the same sensor at the same resistive overheat ratio of 0.2 but different operation mode are shown in Fig. 5. The figure shows that the top curve at CT operation mode has a higher sensitivity than the bottom one at CC mode. If we replot the results in Fig. 6 as the heating power in the sensor divided by the temperature difference vs. the one third power of the shear stress, it can be seen that the calibration exhibits a linear relationship. This is consistent with the theoretical prediction by En.(4). Similar results can also be obtained for CC operation.

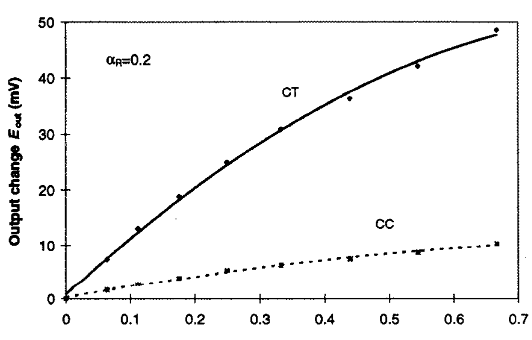


Fig. 5 The shear-stress calibration results of the sensor at the same overheat ratio of 0.2 but different operation mode, CC and CT, respectively.

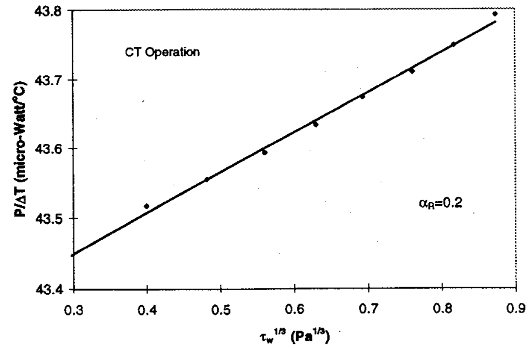


Fig. 6 The replotted results of Fig. 5 at CT mode.

3. Temperature Compensation

The temperature effect of the micro sensors at a fixed free stream velocity (corresponding to a fixed shear stress) is observed. Figs. 7 (a) and (b) show the voltage output change vs. the flow temperature variation at different resistive overheat ratios for both CC and CT operation. In the figure, the slope for each case representing the temperature sensitivity of the sensor is also given.

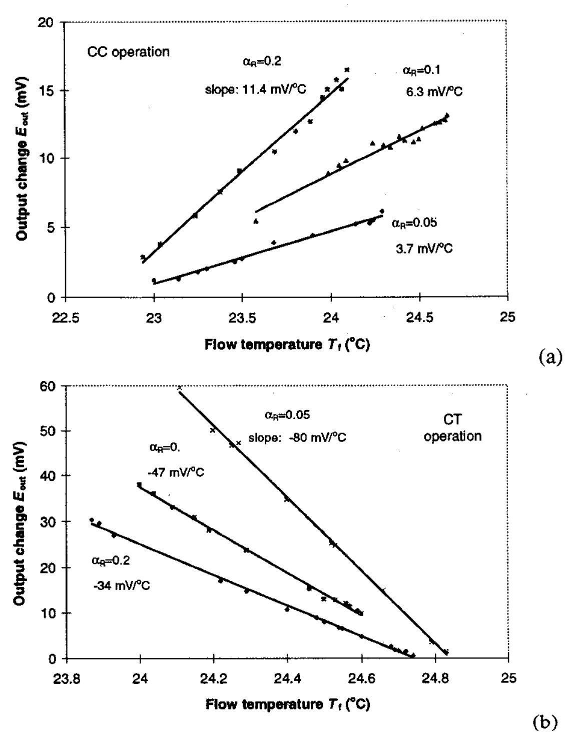


Fig. 7 The temperature effect of the sensor at different overheat ratio for both CC (a) and CT (b) operation.

Based on the above temperature sensitivity results, the temperature effect can be compensated by either a software method or a specially-designed circuit as shown in Fig. 8 for the CT operation. The main difference between this circuit and the previous one in Fig. 3 (b) is op-amps A2 and A3. The op-amp A3 is for the temperature compensation and A2 is for amplification and DC shifting. Another on-chip poly-silicon sensor (named cold-film sensor, it is operated at small current so that its heating effect is negligible) is used to pick up the flow temperature signal. This signal is fed to the circuit through op-amp A3 and then compensated with the signal from the brunch circuit A1. The comparison results with and without temperature compensation at CT mode (resistive overheat ratio of 0.1) is shown in Fig. 9 and it can be seen that the absolute temperature sensitivity (the slope of the line) is decreased from 47 mV/°C to 1 mV/°C after the compensation. By tuning the gain between the input from the cold-film sensor and the output carefully, better results can be obtained. It should be pointed out that all output voltages have been normalized to the output E_{out} of the first stage(A1). This compensation circuit is applicable to the multi-channel circuit operation. In other words, only one cold-film sensor is needed for multi-channel hot-film sensor operation. Similarly, this temperature compensation configuration is also suitable for CC operation.

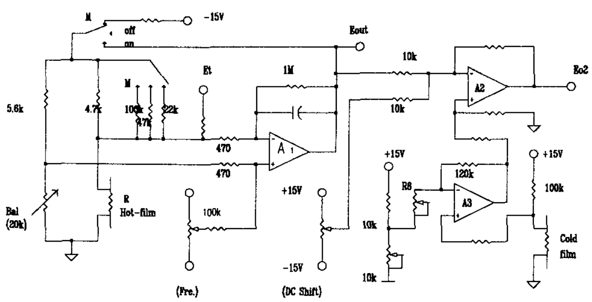


Fig. 8 The temperature compensation circuit for the CT operation of the sensor.

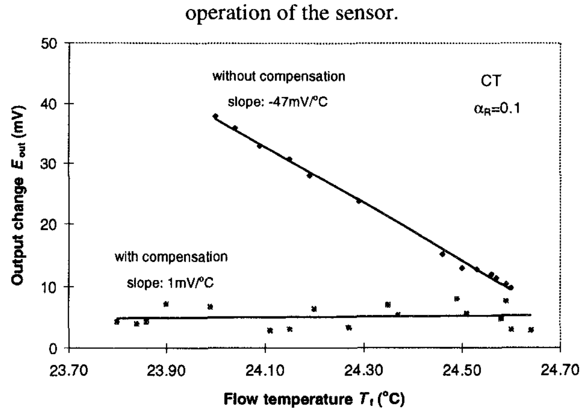


Fig. 9 The temperature compensation results of the sensor at overheat ratio of 0.1 and the CT mode.

V. CONCLUSIONS

The micromachined hot-film shear-stress sensors have been designed and fabricated by micro-machining technology. Extensive experimental results show that the micro shear stress sensor at the constant-temperature operation mode can reach a cut-off frequency of 70 kHz, and a shear stress sensitivity of 70 mV/Pa. The temperature compensation of the sensor has also been characterized.

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