A MICROMACHINED THREE-AXIS GAS INERTIAL SENSOR BASED ON BIDIRECTIONAL THERMAL EXPANSION FLOW

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ABSTRACT

This paper reports a novel micromachined three-axis gas inertial sensor based on the bidirectional thermal expansion flow. Eight heaters and eight thermistors form a "cross-shape" network to generate bidirectional thermal expansion flows for the thermos-resistive sensing of each thermistor. Thus, the Z-axis angular rate and X/Y-axis acceleration can be sensed simultaneously with a sensitivity of 1.370mV/º/s within the range of [-3240º/s, +3240º/s], 2.183V/g and 1.916V/g within the range of [-1g, +1g], respectively. The couplings between X/Y acceleration measurements have decreased to 0.678% and 2.924% respectively.

INTRODUCTION

In the recent two decades, the inertial sensor based on the gas medium instead of the rigid proof mass has drawn much attention due to its advantages of easy fabrication, high shock resistance, and large measurement range [1-6]. Among the gas inertial sensors, the thermal-expansion-flow inertial sensor generates the gas stream by transient temperature change of the heaters. Compared with the gas inertial sensors based on the natural convection, it can efficiently suppress the effect of the external linear acceleration and significantly reduce rotation-acceleration coupling effect.

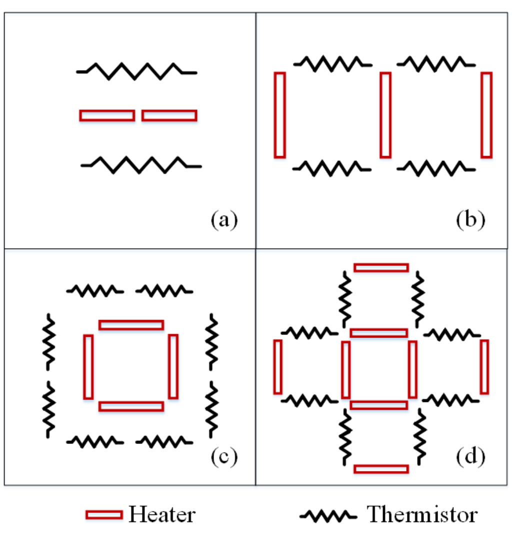

Figure 1: Configuration of the heaters and thermistors for different thermal-expansion-flow inertial sensors: (a) Leung's work [1] (b) Zhu's work [2]; (c) Chang's previous work [3]; (4) this work.

Leung's group [7] presented a thermal-expansion-flow gyroscope which generates an oscillatory gas stream by a parallel configuration of heaters and thermistors (Figure 1(a)). Zhu' group [8] developed a two-axis inertial measurement by using a new configuration (Figure 1(b)). We demonstrated a three-axis inertial measurement by using a square configuration (Figure 1(c)) [9]. However, our previous work used the unidirectional expansion flow for measurement, which will cause a big coupling between different axes. In order to reduce this coupling, we propose a new configuration to generate bidirectional thermal expansion flow for the thermo-resistive sensing of each thermistor. It can also realize the measurements of Z-axis angular rate and X/Y-axis acceleration simultaneously while couplings between multi axes rotation and acceleration are able to be suppressed effectively.

WORKING PRINCIPLE OF THE SENSOR

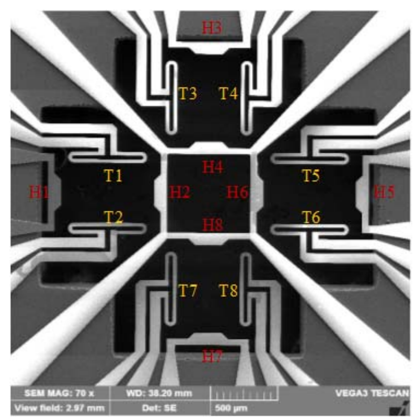

Figure 2: SEM graph of the sensing chip.

The sensor's structure shown in Figure 1(d) is divided into four measurement units distributed symmetrically along the two perpendicular coordinate axes and each unit has a pair of heaters and thermistors. The whole structure of the sensing chip is shown as the SEM graph in Figure 2. Taking the example of a unit, heaters H1 and H2 are separately driven by two same frequency square waves with a 90 degree phase difference and a pulse duty cycle of 50% as shown in Figure 3. The push-pull thermal expansion flow (Figure 4(a), (b)) is generated by alternately heating and cooling the opposite heaters. Both thermistors T1 and T2 are used to detect the resistance change caused by the temperature change. Due to the usage of this asynchronous driving mode, the formed flow can move faster in two orientations and symmetrically in the chamber. Thus, a higher output sensitivity and a better suppression to cross coupling can be achieved.

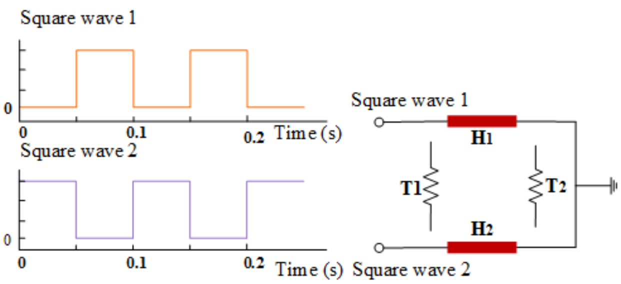

Figure 3: Driving square waves for heaters H1 and H2.

For sensing the angular rate around Z-axis applied, the gas flow would deflect along the direction of Coriolis force and cause the temperature difference ΔT between thermistor T1 and T2. Based on the thermo-resistive effect and the principle of Wheatstone bridge, the resistance change of thermistors is able to be converted to the change of output voltage. The corresponding formulation for measurement of angular rate can be expressed as bellow:

$$V_{out-Gyro} = \frac{\alpha \Delta T_{Gyro-\omega z}}{4} V_{cc} \tag{1}$$

where α is the temperature coefficient of resistance of thermistors and V_{cc} is the supply voltage for Wheatstone bridges.

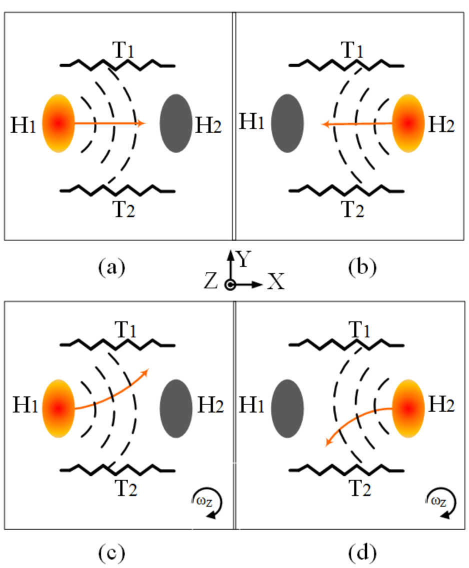

Figure 4: Operating principle diagram of angular rate measurement. (a) H1 heats up and H2 cools down without rotation; (b) H1 cools down and H2 heats up without rotation; (c) H1 heats up and deflection of gas flow with a rotation around Z-axis; (d) H2 heats up and deflection of gas flow in with a rotation around Z-axis.

When a linear acceleration applied along X/Y-axis as shown in Figure 5, the thermal expansion stream will relatively move in the opposite direction of input linear acceleration which induce the temperature difference of opposite thermistors. Similarly, the corresponding transformation of dual-axis acceleration measurement can be expressed as equation:

$$V_{out-Ax/Ay} = \frac{\alpha \Delta T_{acc-x/y}}{4} V_{cc} \tag{2}$$

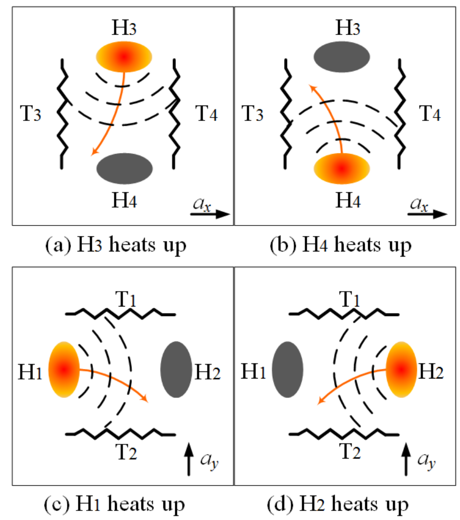

Figure 5: Operating principle diagram of X/Y axis acceleration measurements. (a) & (b) deflection of gas flow in the presence of X-axis linear acceleration; (c) & (d) deflection of gas flow in the presence of Y-axis linear acceleration.

The decoupling solution to Z-axis angular rate and X/Y acceleration simultaneously can be deduced as shown in Figure 6. R_{T1}, $R_{T2,}$ R_{T3}, R_{T4}, R_{T5}, R_{T6}, R_{T7}, R_{T8} are sensing resistors in four units distributed in the way as shown in Figure 2. And R_{ref} is the reference resistor to constitute the Wheatstone bridge and has the same resistance with origin value of thermistors. When the sensor rotates with an angular rate ω_z, the total temperature change of eight thermistors can be calculated as the following formula (3):

$$\begin{aligned}\Delta T_{Gyro-\omega z} = {} & T(R_{T1}) - T(R_{T2}) + T(R_{T4}) - T(R_{T3}) + \\ & T(R_{T6}) - T(R_{T5}) + T(R_{T7}) - T(R_{T8})\end{aligned} \tag{3}$$

where $T(R_{Ti})$ is the temperature value of the corresponding thermistor R_{Ti}, i=1,2,3…8.

With a linear acceleration input a_x, two pairs of detective resistance T_3, T_4 and T_7, T_8 are used to detect temperature changes and the corresponding formula (4) is given as :

$$\Delta T_{acc-x} = [T(R_{T7}) - T(R_{T8})] - [T(R_{T4}) - T(R_{T3})] \tag{4}$$

Similarly, when a linear acceleration a_y is applied, the temperature changes of thermistors T1, T2 and T5, T6 can be expressed as equation (5):

$$\Delta T_{acc-y} = [T(\mathrm{R_{T6}}) - T(\mathrm{R_{T5}})] - [T(\mathrm{R_{T1}}) - T(\mathrm{R_{T2}})] \qquad (5)$$

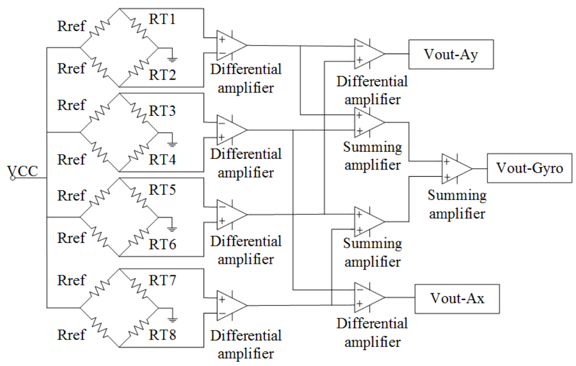

Figure 6: Schematic diagram of the read-out circuit.

FABRICATION PROGRESS

This sensor chip is fabricated in a SOI technology and the fabrication process flow is shown in Figure 7. The SOI chip consists of three layers, i.e. p-type device layer, silicon oxide, and handle layer as shown in Figure 7(a). First, the backside handle layer is etched by inductive coupled plasma (ICP) etching. Through buffered oxide etch (BOE) etching, the thick SiO_2 layer is etched off as shown in Figure 7(b). Next, Aluminum (Al) layer is sputtered on the p-type device layer and used as Al anchors after wet etching as shown in Figure 7(c). Then, thermistors are produced by ICP etching the device layer as shown in Figure 7(d) and the sensing chip is fabricated at this step. Then the chip is aligned and fixed on the board of ceramic shell as shown in Figure 8 before thermistors are connected to pins of shell with bonding wires. Finally, sulfur hexafluoride (SF_6) gas is sealed in the ceramic package.

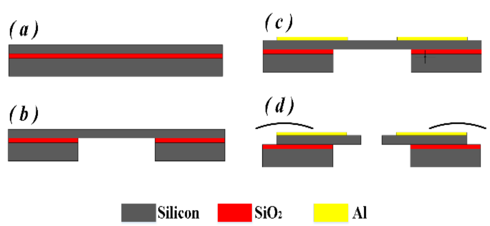

Figure 7: The fabrication process flow of the SOI technology.

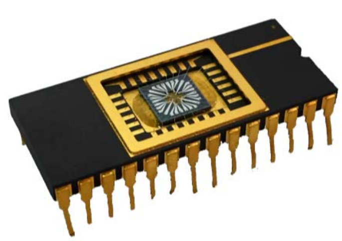

Figure 8: The package of the sensing chip.

EXPERIMENTS

The experiments are performed on a rotation table for the angular rate measurement and a rotary dividing head with a resolution of ±1° for the acceleration measurement. The driving signals for heaters are 15V, 50% duty cycle and 10Hz square wave. Figure 9 shows the output of angular rate with the rotation table spinning around Z-axis from -3240°/s to +3240°/s. There still exists the output voltage of X/Y acceleration induced by the coupling effects from the Z-axis rotation which are both around 7%.

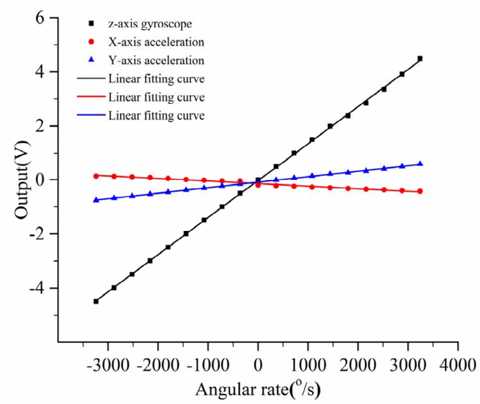

Figure 9: The output voltage of the Z-axis gyroscope versus applied angular rate and the corresponding coupling on X/Y axis acceleration output.

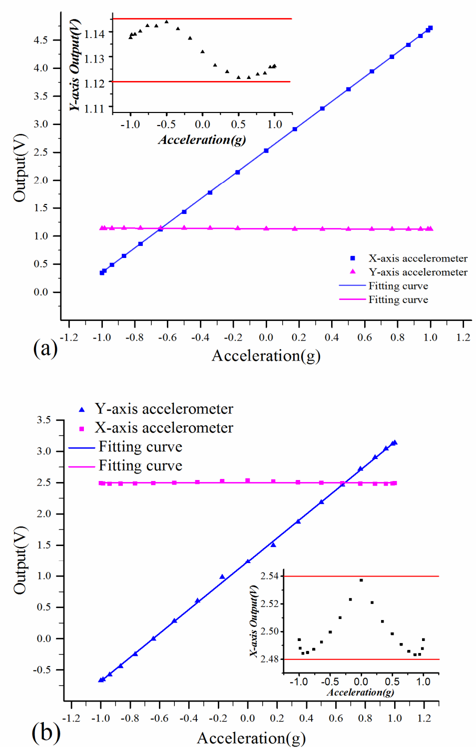

Figure 10: The output voltage of the X/Y-axis accelerometer and corresponding coupling between them. (a) X-axis accelerometer; (b) Y-axis accelerometer

The dual axis acceleration measurements are shown in Figure 10 when the dividing head rotates from -90° to 90° with a step of 10°. It can be seen that the coupling between the two acceleration measurements has decreased to 0.678% and 2.924%, respectively.

As listed in TABLE I, sensitivity and nonlinearity of Z-axis gyroscope and X/Y-axis accelerometer are calculated respectively.

Table 1. Test results of the sensor

Performance	3-DOF Measurement		
	Z-axis gyroscope	X-axis accelerometer	Y-axis accelerometer
Range	[-3240, +3240] °/s	[-90 °, +90 °]	[-90 °, +90 °]
Sensitivity	1.370 mV/°/s	2.183V/g	1.916V/g
Nonlinearity	3.086%	0.681%	4.142%

CONCLUSION

A novel multi-axis measurement inertial sensor based on bidirectional thermal expansion principle is proposed and verified in this paper. It can realize the measurement of Z-axis angular rate and X/Y-axis acceleration simultaneously. The test results illustrate the sensor can detect one-axis angular rate with a sensitivity of 1.370mV/°/s in the range of ±3240°/s. Particularly, when the sensing chip is used as a dual-axes accelerometer, the coupling effect of acceleration between X/Y axis can be suppressed well in the range of [-1g, +1g].

ACKNOWLEDGEMENTS

This work was supported in part by the National Natural Science Foundation of China under Grant 61273052, Shaanxi Science and Technology Co-ordination and Innovation Project (2016KTCQ01-48) and the 111project under Grant B13044.

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