A MEMS HYBRID INERTIAL SENSOR BASED ON CONVECTION HEAT TRANSFER

Rong Zhu[1], Yan Su[2], Henggao Ding[1]
[1] Dept. of Precision Instruments and Mechanology, Tsinghua University, Beijing, China, zrwzwyj@sh163.net
[2] Southeast University, Nanjing, China

ABSTRACT

This paper presents a micro electromechanical hybrid inertial sensor based on convection heat transfer. The sensor configuration consists of a small silicon etched cavity, a suspended central heater and four suspended thermistors, all of which are packaged in a hermetic chamber. The sensor has similar configuration with known thermal accelerometers, but is different because it can sense dual axis accelerations and single axis angular rate. The working principle of the sensor, the numerical simulations of the convection flow and a primary experiment results are presented.

Keywords: Inertial sensor, Convection heat transfer, Micro electromechanical system (MEMS)

INTRODUCTION

Most micromachined inertial sensors usually used a mechanical structure including a solid proof mass attached to springs [1]. For example, several micromachined vibrating gyroscopes have been demonstrated, including vibrating shells [2], tuning-forks [3], and vibrating beams [4].

This paper reports for the first time on the preliminary design and analysis of a novel micromachined angular rate sensor that measures temperature gradients induced by the Coriolis acceleration acting on a gas flow sealed in a small chamber. Novelties also consist that the sensor acts not only as an angular rate sensor, but also as a dual-axis accelerometer. The design incorporates the recent advances in micromechanical thermal accelerometer [5,6,7] with micromachined vibrating gyroscopes to realize a low-cost, thermo-fluidic hybrid inertial sensor system. Since it does not require a solid proof mass and the gas proof mass imposes much less force on the mechanics of the sensor when accelerating, undergoing high shock and strong vibration and is prospective in applications in harsh environment.

OPERATION AND DESIGN

The hybrid sensor system under consideration is based on the interaction of inertial and thermal properties in a laminar, internal chamber flow. The sensor has a similar configuration with a thermal accelerometer, which is comprised of a small silicon etched cavity with the size of 2mm×1mm×0.3mm (X×Y×Z) shown in Fig. 1. Where X and Y are the central axes of the cavity surface. A suspended central heater placed at X-Y plane of the cavity (named as work plane) heats up and lowers the density of the surrounding gas. Four suspended thermistors oppositely placed at the same work plane measure the local gas flow. The sensor is packaged in a sealed chamber to prevent external air flow from disturbing the sensor operation. When an acceleration is applied along Z-axis and the heater heats up, the gas flow in the region of the hermetic chamber is represented schematically in Fig. 2(a) and (b). Fig. 2(b) shows the gas flow at work plane displays opposite symmetrical characteristic.

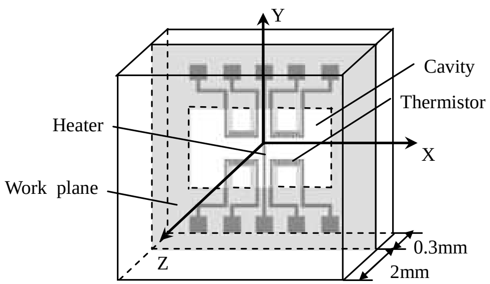


Fig. 1. Schematic view of the sensor configuration in a sealed chamber

The principle of detecting acceleration in X and Y widely investigated [5,6,7]. In this paper, we only focus on the angular rate detection.

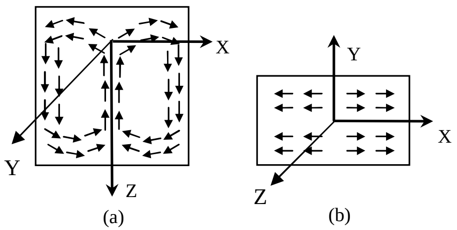


Fig. 2. Schematic view of the gas flow in region of hermetic chamber

In work plane, the input angular rate rotation $\vec{\omega}_z$ of the sensor around Z axis induces Coriolis acceleration $\vec{a}_y$ normal to the direction of flow $\vec{v}_x$

$$\vec{a}_y = 2\vec{\omega}_z \times \vec{v}_x \tag{1}$$

where $\vec{v}_x$ represents the flow velocity in X direction at work plane. This Coriolis acceleration moves the opposite flows $\vec{v}_x$ to deflect in the opposite direction of Y as shown in Fig. 3(a). The deflection causes opposite cooling effects between pair of opposite thermistors (i.e. R_{C1} and R_{C2} or R_{W1} and R_{W2}), and as a result, the resistances of R_{C1} and R_{C2} (also for R_{W1} and R_{W2}) change oppositely. Wheatstone bridge circuit as shown in Fig. 3 (b) converts the two pairs of resistance changes (R_{C1}-R_{C2} and R_{W1}-R_{W2}) to the output voltage changes ΔR_C and ΔR_W, respectively. Since the opposite symmetric flows in X direction are deflected in the opposite direction of Y due to Coriolis acceleration. Therefore ΔR_c is proportional to the angular rate (ω_z) of the rotation with respect to the Z axis, whereas ΔR_W is proportional to the inverse angular rate ($-\omega_z$) of the rotation with respect to the Z axis. The difference δv between ΔR_C and ΔR_W (ΔR_C-ΔR_W= δv) is thus proportional to the angular rate $2\omega_z$. This differential processing by using opposite symmetric flows in X direction can successfully eliminate side-effect of non-Coriolis accelerations in Y direction that move the opposite flows $\vec{v}_x$ to deflect in the same Y direction and are eliminated via ΔR ΔR

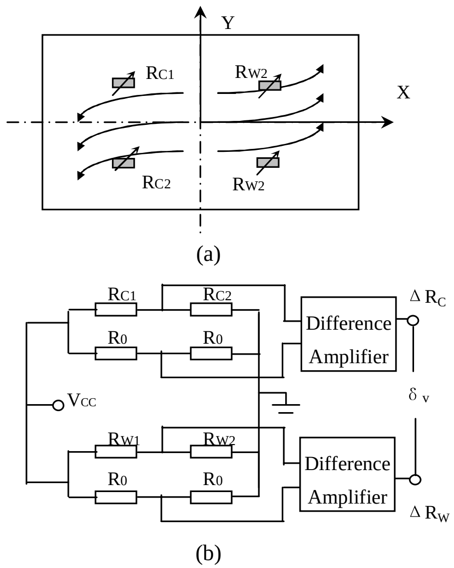


Fig. 3. The opposite flows in X direction are deflected in the opposite directions of Y due to the Coriolis effect, and Wheatstone bridge circuit outputs the angular rate

NUMERICAL SIMULATION AND ANALYSIS

A CFD model is developed as following to describe the three-dimensional convection flow in the sensor chamber, which can be solved to obtain the transient velocity, temperature and pressure of gas in the chamber.

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = 0 \tag{2}$$

$$\frac{\partial(\rho \vec{v})}{\partial t} + \rho \vec{v} \cdot \nabla(\vec{v}) = -\nabla(p) + \rho \vec{a} + \nabla(\mu \cdot \nabla(\vec{v})) \tag{3}$$

$$\frac{\partial(\rho c T)}{\partial t} + \nabla(\rho c \vec{v} T) = Q - W + k \cdot \nabla^2(T) - \nabla(p \vec{v}) \tag{4}$$

$$\rho = \frac{p}{R \cdot T} \tag{5}$$

where $\vec{v}, \vec{a}, \rho, p, \mu, T, c, k, R, Q$, and W refer to the velocity vector, acceleration vector, gas density, pressure, dynamic viscosity, temperature, gas specific heat, thermal conductivity of gas, gas constant, heat generation and wall heat transfer, respectively. The vector operator ∇ is defined as $\nabla \equiv i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z}$. The wall heat transfer is given in terms of the boundary temperature refer to heat transfer coefficient, temperature of gas and temperature of the wall, respectively.

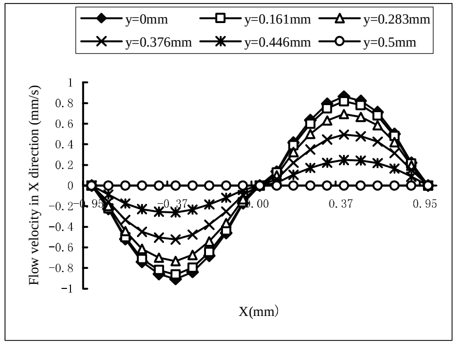


Fig. 4. Flow velocity profile in X direction at work plane

The numerical simulation of the flow velocity was performed by using ANSYS software. Fig. 4 shows the flow velocity profile in X direction at the work plane when 1g (9.8m/s^2) acceleration is applied along Z axis of the sensor, where y represents the distance from X axis. According to the above analysis, the convection flow is due to the local acceleration applied and the temperature difference between the gas and the wall. And the angular rate detection is based on the opposite symmetric flows along X axis at work plane that are induced by the acceleration in Z direction. However the acceleration in the X direction will perturb the symmetry of gas flow. When 1g acceleration is applied in Z direction and additional acceleration Ax is applied in X direction, the asymmetric flow velocities in X direction is shown in Fig. 5, which indicates that the flow in X direction is accelerated so as to break the opposite symmetry of the flows at the work plane induced by the acceleration applied in Z direction. Fortunately, we found when we differenced the X velocities between the two opposite flows in X direction, the difference of velocity was almost unchanged and independent of the accelerations applied in X direction. Fig. 6 shows the difference of X velocities between the two opposite flows in X direction at the work plane when the 1g acceleration and the additional acceleration Ax are applied along Z-axis and X-axis, respectively. The result reveals that the above differencing approach of detecting angular rate of the rotation using opposite symmetric flows along X axis at work plane is still valid even when the accelerations in X direction are existent because the measurement of the angular rate is relied on the difference between two opposite symmetric flows at the work plane.

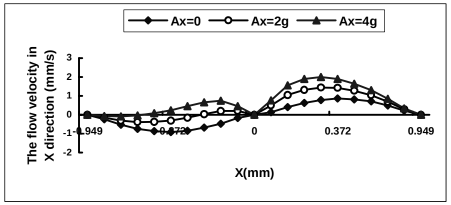


Fig. 5. The flow velocities in X direction at y=0mm when the 1g acceleration is applied along Z-axis and the additional acceleration Ax is applied along X-axis

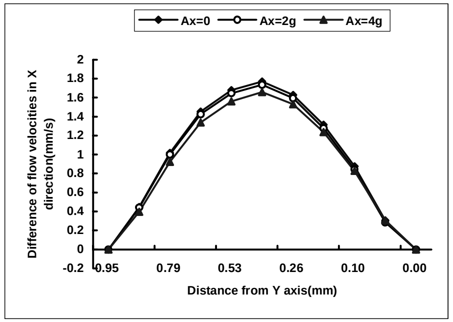
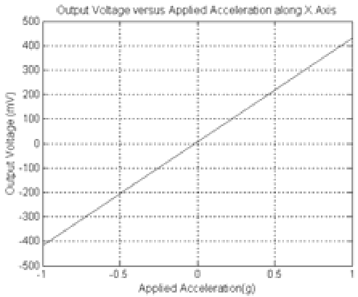


Fig. 6. Difference of X velocities between the two opposite flows in X direction at the work plane when 1g acceleration is applied along Z and the additional acceleration Ax is applied along X

The simulation results also show that the acceleration in Z direction correlates with the X velocity of the flow at the work plane so as to affect the scale factor of the sensor. As a result, the acceleration in Z direction must be known and employed as a parameter to determine the scale factor of the sensor for detecting the angular rate of the rotation around Z axis.

PRIMARY EXPERIMENTAL RESULTS

A prototype of the sensor was fabricated based on the same technology used for thermal accelerometers [5]. To test the sensing performance, the prototype was placed on a turntable and connected to a signal amplifier. The acceleration input ranged from –1g up to +1g was applied to X direction, then to Y direction. The output voltage over the applied acceleration was measured. Fig. 7 presents the results. Then the angular rate input ranges from -600 degree/sec up to +600 degree/sec was applied around Z axis of the sensor, when the gravity acceleration (9.8m/s^2) is along Z axis. The output voltage over the applied angular rate was measured as Fig. 8.



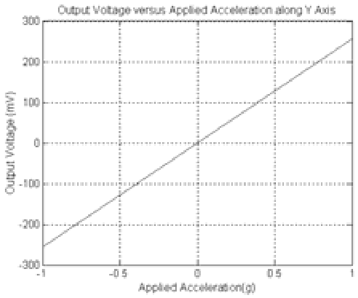


Fig. 7. Experimental results of the prototype for acceleration measurement

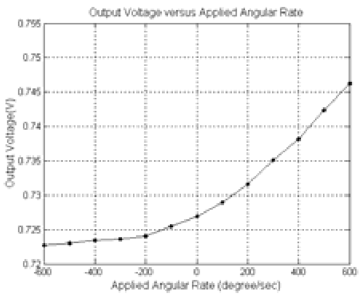


Fig. 8. Experimental results of the prototype for angular rate measurement

CONCLUSION

The concept, the configuration design and flow simulations of a MEMS hybrid inertial sensor based on convection heat transfer are presented. The sensor with a simple configuration can detect dual axis accelerations and single axis angular rate. A primary experiment of prototype is performed to validate the effectiveness of the sensor. The absence of a vibrating proof mass should increase the shock resistance of the thermal sensor, and hence provide greater sensitivity as reported for thermal accelerometers.

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