Modeling and Analysis of Temperature Effect on MEMS Gyroscope

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Abstract

It is well known that temperature variation affects a MEMS device's performance. In this paper, the effect of temperature on the whole MEMS based gyroscope is observed by recording and analysis the zero rate output (ZRO). The effect of temperature on the ZRO comes from material parameter changing and electronic parameter changing.

With temperature changing, the ZRO of the gyroscope suffers from changes of stiffness coefficient of beams, the damping ratio and other parameters [1]. A matlab Simulink model is built to research how much influence the material parameter has on the ZRO. The simulation result shows that material parameter changing induced effects have influence on the ZRO for 0.2% in the range of around room temperature.

Application Specific Integrated Circuit (ASIC) is an important part of a gyroscope. As most ASICs are made by semiconductors like silicon, the features of ASIC components (like output voltage, gain factors and resistance of doped silicon) are temperature sensitive by nature. A model based on a simplified ASIC component of capacitance to voltage converter circuit (C/V circuit) with temperature sensitive parasitic resistances is built to explore how much influence the electronic parameter has on the ZRO. The simulation result shows that electronic parameter changing induced effects have influence on the ZRO for less than 3ppm in temperature range from 273 K to 318 K.

The experiment is conducted by exposing a MEMS gyroscope into a thermal chamber, and the temperature range is from 273 K to 318 K. The experiment result indicates the temperature fluctuation has influence of about 5% on ZRO when the reference is the ZRO at 300 K. Material parameter changing induced effect has the greatest impact on ZRO, and that effect needs to be compensated to improve the ZRO stability of a MEMS gyroscope.

I. Introduction

MEMS gyroscope is a kind of widely used component for obtaining angular velocity in applications like inertial measurement unit (IMU) and cellphones, etc. [2]. MEMS gyros can be divided into many kinds according to their working principle or sensing method, etc. A linear vibration MEMS gyroscope is used in our modeling and experiment.

There have been many articles studying on temperature effects on gyroscopes. Many past studies have characterized the relationship of gyroscope frequency with temperature, and the frequency change is believed to be one of the main reasons to affect ZRO. Temperature variation induced frequency change and phase change can also be used as a thermometer to compensate ZRO [1].

Parasitic resistance and capacitance have great influence on gyroscopes. However, the effect of temperature dependent characteristic of the parasitic resistance on the output of gyroscopes has never been considered [9].

In the following article, the working principles of the MEMS gyroscopes are discussed. Next, material parameters changing induced effects (MPCIE) and electronic parameters changing induced effects (EPCIE) are discussed. At last, the experiment result is compared with the simulation result.

II. Working Principles of the MEMS Gyroscopes

The operation principle of the majority of all existing commercial MEMS vibratory gyroscopes relies on the Coriolis force shown in formula 1[3], which is proportional to the result of the linear velocity of the proof-mass multiplies by the orthogonal angular-rate input. The proof mass and its flexible supporting beams above the substrate are fabricated in silicon-on-insulator (SOI)-based process [4].

$$F_C = -2m \cdot \vec{\Omega} \times \vec{v} \tag{1}$$

Where F_C is the Coriolis force applied to the proof-mass, and m is the mass of the proof-mass, Ω is the angular velocity of the proof-mass, and v is the velocity of the proof-mass.

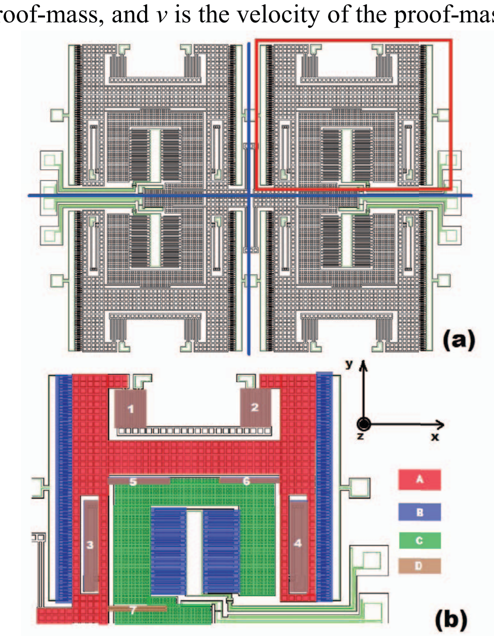

Figure 1. Sketches of the MEMS Part of a Gyroscope.

The sketch of the MEMS part in our experiment gyroscope is shown in Figure1. Fig.1 (b) is an enlarged drawing of the top right part (surrounded by a red rectangle) of Fig.1 (a). It's obvious that Fig.1 (a) is symmetric along the two blue lines (one is vertical, and the other is horizontal), so we could take Fig.1 (b) to illustrate the whole gyroscope.

Fig.1 (b) consists of four main segments (A, B, C and D) emphasized in different colors. Segment A and C are proof-masses that can move in *x* direction, while segment C can move in both *x* and *y* directions. Segment D1, D2, D3 and D4 are flexible beams to support segment A and C above the substrate, and segment D5, D6 and D7 are flexible beams to connect segment C to segment A. Segment B is comb structure capacitance for driving and sensing.

As an inertial component cannot avoid working in a certain degree of vibration environment that will bring small undesired Coriolis response, it's necessary to use an anti-phase system, also known as tuning fork gyroscopes (TFG) shown in Fig.1[5].

There are two identical masses in TFG architecture, which are working in opposite direction and in the same frequency. When the response of two masses is added, the common-mode response of TFG is canceled out. The lumped model TFG is shown below in Fig.2.

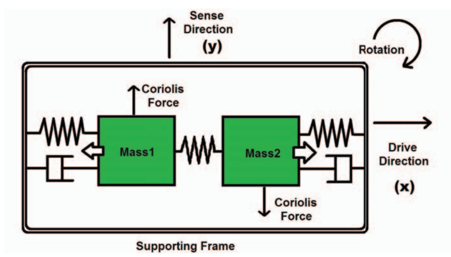

Figure 2. Lumped Model of TFG.

The drive-mode oscillator is comprised of mass1, mass2, suspension beams to allow masses move in *x* direction, actuation electrodes and feedback electrodes. The sense-mode oscillator is formed by masses, supporting beams and sense-mode detection electrodes. The driving forces applied to the masses are usually sinusoidal generated by a closed-loop drive system shown in Fig.3 below.

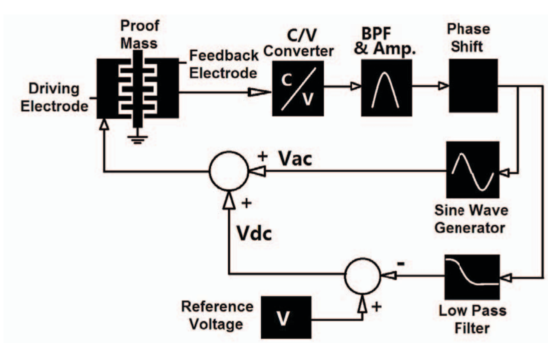

Figure 3. Closed-loop Drive-Mode Oscillator System with AGC.

The overall dynamical system is typically a two degrees-of-freedom (2-DOF) mass-spring-damper system. When the gyroscope is subjected to an extern angular rotation around axis z, a sinusoidal Coriolis force at the same frequency of driving frequency is induced in the direction orthogonal to the drive-mode oscillation.

Even though designing the drive and sense resonant frequency to match is helpful to attain the maximum sensitivity, it's more common that the sense mode is designed to be slightly shifted from the drive-mode to improve robustness.

III. Material Parameter Changing Induced Effects

There has been many articles discussing thermal characteristic of MEMS linear vibration gyroscopes, and most of these articles focus on the change of the size configuration and elastomeric modulus due to the change of the temperature [6]. From the simulation result of Sun, we can see that the change of the amplitude of the driving and detecting mode due to the change of the size of the configuration is very small (within 0.8%)[6]. So we can ignore the effects of configuration's changing, and focus on the effects of elastic modulus's variation.

Temperature variation may influence the elastic coefficient of the supporting beams, thereby the resonance frequency and the amplitude of drive mode.

The change of the silicon's elastic modulus with temperature can be described as follows [7]:

$$E(T) = E_0[1 - k(T - T_0)] \qquad (2)$$

where *E(T)* and E_0 are the elastic modulus of silicon at temperature of T and 300K respectively. T_0=300K, and *k*=70ppm.

The supporting's stiffness coefficient is proportional to the elastic modulus, so the relationship of the stiffness coefficient and temperature is shown as equation (3).

$$K(T) = K_0[1 - k(T - T_0)] \qquad (3)$$

where *K(T)* and K_0 are the stiffness coefficient of silicon at temperature of T and 300K respectively. T_0=300K, and *k*=70ppm.

The drive mode oscillators are two coupled 1-DOF resonators, and each one can be modeled as a mass-spring-damper system. With a sinusoidal drive-mode excitation force, the motion equations along the x-axis are

$$m_1\ddot{x}_1 + c_d\dot{x}_1 + k_c(x_1 - x_2) + k_d x_1 = F_d \qquad (4)$$

$$m_2\ddot{x}_2 + c_d\dot{x}_2 - k_c(x_1 - x_2) + k_d x_2 = -F_d \qquad (5)$$

$$F_d = \sin(\omega_d t) \qquad (6)$$

where m_1 and m_2 are the mass of mass1 and mass2 in Fig.2 respectively, and x_1 and x_2 are the displacement of each mass. k_c is the coupling spring's stiffness coefficient, and k_d is the supporting beams' stiffness coefficient. F_d is a sinusoidal drive force, and it's sign reversing in equation (4) and equation (5), which indicate the motion of two masses are anti-phase. There are modules like AGC and PLL in our experiment gyroscope to enable drive mode resonant stable in both amplitude and phase, so we can believe that temperature has little impact on the phase.

The Q of gyroscope and pressure has a relationship: if the pressure increases for four orders of magnitude, the Q decreases for one order of magnitude. The pressure is proportional to the temperature in a MEMS package. Q is defined as

$$Q = \frac{1}{2\xi} = \frac{\sqrt{km}}{c} \tag{7}$$

where k is the stiffness coefficient, c is the damping coefficient, and ξ is the damping ratio. Generally, the variation of k vs. temperature is smaller than the variation of c vs. temperature. The relationship of damping ratio vs. temperature is

$$c(T) = c_0 \cdot 10^{\frac{\ln(T/300\,\mathrm{K})}{4\ln(10)}} \approx c_0 \cdot 1.28^{\ln(T/300\,\mathrm{K})} \tag{8}$$

where c_0 is the damping coefficient at 300 K, and T is temperature in degree of Kelvin.

To solve these equations at different temperature, we use matlab Simulink. The model we build is shown below in Fig.4.

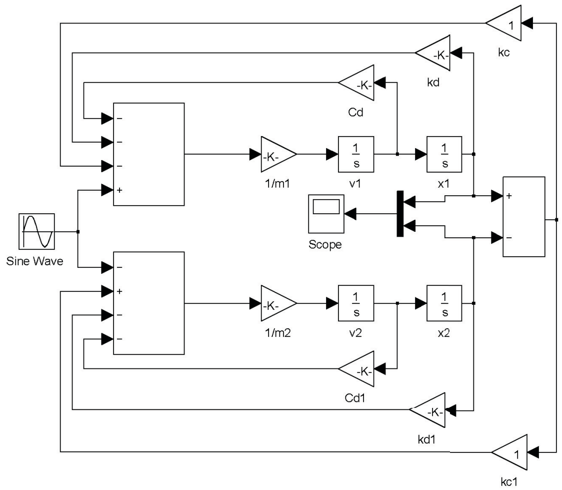

Figure 4. The Simulink Model of Drive-Mode Oscillator.

One single gyroscope cannot work, and gyroscopes need suitable circuits and packaging to work well. The packaging enables the temperature of gyroscopes to vary in a range of nearby room temperature. The temperature range in our simulation is set to be from 0 ℃ to 45 ℃ with the interval being 5 ℃.

The elastic module at 300 K is set as a reference, so the value can be set to be one, and likewise the value of damping coefficient at 300 K can be set to be one as a reference. These values can be calculated before simulation, and the results are shown below in Tab.1.

Table 1. Relative values of elastic module and damping coefficient nearby room temperature

Temp. (K)	273	278	283	288
Elastic module	1.0019	1.0015	1.0012	1.0008
Damping coefficient	0.9770	0.9814	0.9857	0.9900
Temp. (K)	293	298	303	308
Elastic module	1.0005	1.0001	0.9998	0.9994
Damping coefficient	0.9942	0.9984	1.0025	1.0065
Temp. (K)	313	318		
Elastic module	0.9991	0.9987		
Damping coefficient	1.0105	1.0145		

The parameters used in Simulink take value as below.

$$m = 8.5\times10^{-8}\,kg \tag{9}$$

$$k_{d0} = 215 \quad N/m \tag{10}$$

$$k_{c0} = 20 \quad N/m \tag{11}$$

$$c_{d0} = 6\times10^{-6} \quad N\cdot s/m \tag{12}$$

where m is the mass of the drive-mode proof mass. k_{d0} and k_{c0} are the elastic module of supporting beams and coupling beams at 300 K, respectively. c_{d0} is the damping coefficient at 300 K.

The Simulink simulation result (Fig.5) shows that the amplitude of drive-mode oscillator is 4.0071 μm at 300 K. The amplitude would change with temperature, and the relationship is almost linear. In the range of nearby room temperature, the amplitude variation ratio changes from -0.2% at 273 K to 0.14% at 313 K. In Fig.5, the scatter plot is the simulation result, and the red solid line is the fitting curve with a slope of 0.2918 *nm*/K.

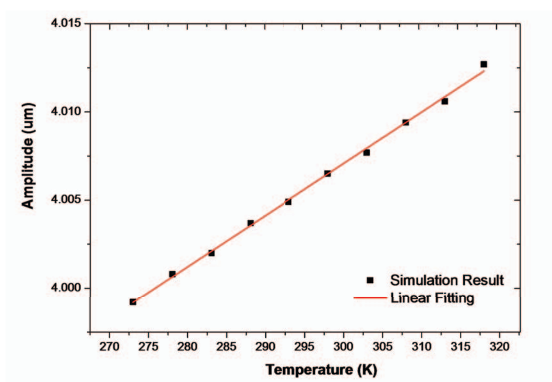

Figure 5. Amplitude vs. Temperature.

IV. Electronic Parameter Changing Induced Effects

There are many comb structures in the MEMS part of the gyroscope, and these structures are capacitances for three different usages. Three usages for capacitances are driving, feedback and sensing. Driving capacitance is designed to generate the electrostatic force to drive proof masses to vibrate. Feedback capacitance is designed to obtain the displacement of driving electrodes, which is helpful for closed-loop control of the driving oscillator. Sensing capacitance is designed to detect the displacement of proof masses in Coriolis force direction.

However, the electrodes of capacitances in most gyroscopes are not connected to ASIC pads directly. The components to connect capacitance electrodes and ASIC pads are doped silicon and gold wires usually. The resistance of gold wire is quite smaller than that of doped silicon, so that the resistance of gold wire is ignored in most articles. It is also common that the resistance of doped silicon is ignored to simplify analysis.

The pads of the gyroscope in our experiment are placed along one edge of the MEMS part, and this kind of design lengthens the doped silicon conductor trace line, and finally results in larger resistance.

C/V converter circuit is a kind of circuit that converts capacitance variation into voltage variation. A typical C/V circuit schematic is shown below in Fig.6.

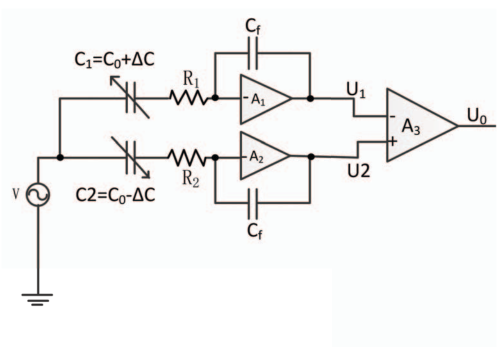

Figure 6. C/V Circuit with Parasitic Resistance

where V is a sinusoidal voltage source, C_1 and C_2 are sensing capacitances of MEMS, C_f is a feedback capacitance in ASIC, and A_1 A_2 A_3 are ideal amplifiers. R_1 and R_2 are parasitic resistances in MEMS structure, and they are zero in ideal situation.

C_1 and C_2 vary in anti-phase to reject the common mode signal and increase the output signal. The output voltage U_0 is proportional to ΔC (the variation of feedback capacitance of MEMS) as shown in Equ.13.

$$U_0 = \frac{2\Delta C}{C_f} \cdot V \cdot \frac{1}{\sqrt{1+(2\pi f C_0 R)^2}} \tag{13}$$

In equation (13), f is the frequency of carrier wave, which is a few times the driving mode frequency (8000Hz in our experiment gyroscope), and in our simulation f is 50000 Hz. C_0 is the capacitance of sensing capacitance at static state, and its value is usually in the level of pF and in our simulation we can regard it as 10pF. The equation also indicates that in ideal situation (R=0), the circuit gets its largest output voltage.

The resistivity of highly doped silicon is around 0.02 Ω·cm [8]. The length of highly doped silicon conductor-trace-line is around 3 mm and the width is around 5 μm. The aspect ratio of MEMS gyroscope is about 10, so the thickness is about 50 μm. Based on the data provided, we can calculate that the parasitic resistance is about 2400 Ω.

The mismatch ratio is defined to be the real output voltage to the ideal output voltage ratio, so we get equation (14).

$$h = \frac{1}{\sqrt{1+(2\pi f C_0 R)^2}} \tag{14}$$

From equation (14) we can see that the real output voltage is always smaller than that of ideal.

The resistivity of highly doped silicon changes with temperature and the temperature coefficient is up to 0.2%/℃ [9]. The simulation result is shown in Fig. 7. The scatter plot is the simulation result, and the red solid line is the fitting curve.

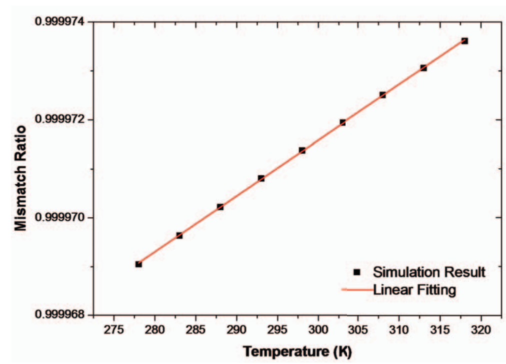

Figure 7. Mismatch Ratio vs. Temperature.

Mismatch ratio changes with temperature slightly, and their relationship is linearity with a slop of about 0.146 ppm/K. The mismatch ratio changes by from 0.0003% at 273 K to -0.0002% at 318 K, relative to the mismatch ratio at 300 K.

V. Experiment Results

The output of the gyroscope in out experiment is analog voltage within the range from 0.5 V to 4.5 V. The ideal ZRO is 2.5 V at room temperature (300 K). The gyroscope PCB board is placed in thermal cycling chamber, and the data processing circuit connected to the gyroscope by wires is placed outside the chamber.

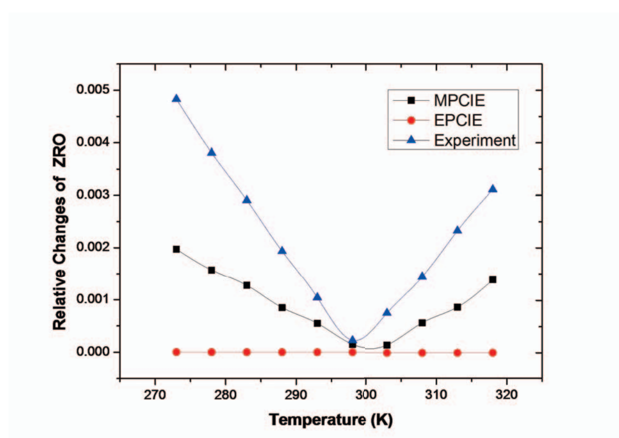

Figure 8. Comparison between Simulation and Experiment.

The results are shown in absolute value of relative changes of ZRO, and the value at 300 K is selected as the reference ZRO to calculate ZRO drift. The trends of MPCIE and EPCIE match the experiment result well.

VI. Conclusions

In this article, two models are built to analysis ZRO drift with temperature variation. The simulation result shows that material parameter changing induced ZRO drift is within 0.2% and is the main reason of ZRO drift nearby room temperature. Electronic parameter changing induced effects has very little influence on ZRO drift of about 0.0003% which is three orders magnitude smaller than that of MPCIE. In the range of room temperature (273 K ~ 318 K), the relationship of ZRO and temperature is linear, so are MPCIE and EPCIE.

VII. Acknowledgments

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