A Novel Temperature Compensation Method for a MEMS Gyroscope Oriented on a Periphery Circuit

Regular Paper

Huiliang Cao¹, Hongsheng Li¹*, Xia Sheng¹, Shourong Wang¹, Bo Yang¹ and Libin Huang¹

¹ School of Instrument Science and Engineering, Key Laboratory of Micro Inertial Instrument and Advanced Navigation Technology of Ministry of Education, Southeast University, Nanjing, People’s Republic of China

* Corresponding author E-mail: hsli@seu.edu.cn

Received 20 Dec 2012; Accepted 26 Jul 2013

DOI: 10.5772/56759

© 2013 Cao et al.; licensee InTech. This is an open access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract This paper investigates temperature compensation methods used for the scale factor and bias of the MEMS gyroscope within the temperature range from -40°C to 60°C. The structure and periphery monitor circuit are introduced. Then the determinant elements of the MEMS gyroscope’s scale factor are analysed and the results indicate that scale factor is directly proportional to drive amplitude and sense loop gain and is inversely proportional to the frequency gap between two modes. After that, the compensation methods are proposed, the thermal resistor’s positive temperature coefficient (tempco) is utilized to calibrate the scale factor’s tempco through regulating the drive mode amplitude and the sense loop gain, and each method is applied respectively and the results are contrasted. The test results of the two specimens express that the most effective compensation method could decrease the scale factor’s tempco from 693ppm/°C (640ppm/°C) to 9.70/°C (12/°C) improving it by 90.7% (88%). Repeat tests are performed based on two specimens to prove the repeatability and reproducibility of the methods.

Keywords Temperature Compensation, Scale Factor, Bias, MEMS Gyroscope

1. Introduction

MEMS gyroscope is a silicon-based sensor which can detect input angular rate information through the Coriolis acceleration. Due to the advantages of its low cost and low power consumption, micro volume, tiny weight and excellent shock survival capability, the MEMS gyroscope has been applied in many areas, such as: angular velocity measuring systems, micro inertial navigation systems, automobile security systems, consumer electronics and robot control systems (Fei et al. [1]-[2]). The architecture of the MEMS gyroscope is fabricated with silicon, which is a high temperature-sensitive material and its physical
characteristics vary greatly with ambient temperature, meanwhile, the mechanical-thermal noise in the structure can also influence the gyro’s performance (Leland [3]). The MEMS gyroscope’s temperature performance is described in several references: Ferguson et al. [4] indicated that the drive and sense-resonant frequency have a linear relationship with temperature, and the bias’s tempco is 13mV/°C over a range of 35°C to 65°C. Patel et al. [5] designed temperature experiments from -25°C to 125°C with different angular rates and repeated them 500 times; the results showed that the MEMS gyroscope has a significant shift when it works in thermal cycles with a long duration. Sun et al. [6] employed the architecture model of a linear vibrating gyroscope to analyse the influence of slow-changing temperature upon the amplitude and the phase of the drive and sense modes. Liu et al. [7] investigated the relationships between ambient temperature and the MEMS gyroscope’s detection capacities, the dynamic characteristics of which are calculated based on a model. Joo [8] described the influence of temperature on the package of the gyroscope.

A large amount of literatures focuses on improving the gyroscope’s temperature characteristics. The methods in these papers can be summarized as belonging to three different areas:

1. Architecture compensation and material improvement: Trusov et al. [9] presented an architecture which has a higher temperature stability and robustness. Ho [10] presented a temperature compensation method using a silicon L-shaped beam. Tsai [11] presented the structure compensation for a MEMS gyroscope with a disturbance estimator and indicated that the architecture’s imperfect fabrication and asymmetry can also decrease the temperature characteristic. Cao [12] investigated how the gyroscopic structure’s mechanical model is affected by temperature and proposed methods to improve the silicon structure’s temperature robustness. Hou et al. [13] attached two kinds of epoxy material between the architecture substrate and its package to decrease the resonant frequency and the tempco of the quality factor.

2. Software compensation: Zhu et al. [14] processed the output data with a linear compensation algorithm by using the relationship between the temperature inside the gyroscope’s shell and the output data. After the compensation, the tempcos of the bias stability reduce from 229.1°/h/°C to 35.7°/h/°C and this method is fit for gyroscopes with good temperature repeatability and reliability, but which lack instantaneity. Zhang and Wang [15] eliminated the dynamic angular velocity error by using a RBF neural network system. Zhang et al. [16] used a high order polynomial to compensate the bias of a double H quartz tuning fork gyroscope on a digital signal processing platform. The variation of the bias decreases from 300mV to 0.2mV during -40°C to 80°C after the compensation. Fang [17] introduced an integrated electromechanical-thermal error model and employed a least-squares algorithm to compensate the bias drift which is caused by temperature.

3. Temperature-control: Xia et al. [18] proposed a temperature-control system to steady the ambient temperature, which utilizes a BP (Back Propagation) neural network to build the temperature model and a PID control algorithm to compensate and control the gyroscope’s internal temperature. Using that method, the maximum absolute bias in the temperature range -40°C - +80°C is reduced to 0.608°/s from 12.331°/s, and the ambient temperature is restricted to within 0.3°/s when the temperature changes from -20°C to 35°C. Lee et al. [19] investigated on-chip temperature control technology which is based on a micro thermal resister, a heater and a thermal isolate package. After on-chip temperature control, the drive resonant frequency’s tempco decreases to 0.96 ppm/°C (0.22 ppm/°C with additional compensation) from 17.3 ppm/°C.

This paper compensates the tempco of scale factor by changing the drive mode amplitude and sense loop gain, and employs a summator and a thermistor to decrease the bias’s tempco. The method is not mentioned in previous literature and it requires that the devices have a good temperature repeatability and reliability. In consideration of the variation of the bias value after the compensation of the scale factor, the scale factor should be compensated before the bias and the process step for this is illustrated in Figure 1. Firstly, a temperature test is done to describe the scale factor’s temperature curve which is the foundation of the compensation. Then, the parameter values are configured in the circuit with different compensation methods. Next, the temperature tests are arranged to verify the compensation results. Finally, the bias compensation method is implemented based on the most effective scale factor compensation circuit.

Figure 1. Flow diagram of the compensation process
The remainder of this article is organized as follows: section 2 introduces a fully decoupled double mass structure and a monitor peripheral circuit of the MEMS gyroscope, the processes of assembling and testing are mentioned in this section too. In section 3, the components influencing the scale factor are analysed and compensation methods are proposed with their experiment results. Bias compensation and tests are presented in section 4 to verify the method. Section 5 concludes the paper.

2. Structure of the MEMS gyroscope and periphery circuit

The gyroscope contains two parts: the silicon structure which can transform the angular rate information into Coriolis force; the other part is the monitor periphery circuit, which provides the electrostatic force to drive mode and detects the displacement of the sense mode caused by Coriolis force.

2.1 MEMS gyroscope’s structure

The structure used in this paper is fully decoupled and has double mass, as shown in Figure 2.

The two masses are symmetrical and stimulated along the x axis by the electrostatic force from the drive comb electrodes. The amplitude of the drive frame is measured by the drive sense comb electrodes and the displacement caused by the Coriolis force on the y axis is detected by the sense comb electrodes. The two masses vibrate in the anti-phase mode to decrease the sensitivity of the acceleration. The slide-film damping comb can achieve a high quality factor (Q) and mechanical sensitivity. Furthermore, the push-pull drive method is employed to achieve a better drive effect. The structure is fabricated with DDSOG (Deep Dry Silicon On Glass) process technology and an overall photo and a partially enlarged drawing are shown in Figure 3 (Cao [12]).

The equivalent ideal mechanical model of a one mass system is described in Figure 4 (Fei et al. [20]). It includes drive and sense modes, and each mode is a spring-mass-damping system. A fully-decoupled structure could isolate the influence between the two modes and ignore the mechanical quadrature error (Cao [12]).

The movement formulas for the ideal model of the gyroscope architecture can be expressed as:

\[
\begin{aligned}
\dot{x} + c_x \dot{x} + k_x x &= F_d = A_x \sin(\omega_d t) \\
\dot{y} + c_y \dot{y} + k_y y &= -2m_p \Omega_z \dot{x}
\end{aligned}
\]

where \(m_x, m_y, c_x, c_y, k_x\) and \(k_y\) are the equivalent masses, effective damping and stiffness of the drive and sense modes; \(x\) and \(y\) are the displacement of the drive and sense frames; \(F_d\) is the drive force with amplitude \(A_d\) and angular frequency \(\omega_d\); \(m_p\) is the Coriolis mass; \(\Omega\) is the angular rate around the z axis. Define: \(\omega_{ax} = \sqrt{\frac{k_x}{m_x}},\)

\(\omega_{ay} = \sqrt{\frac{k_y}{m_y}}\), \(Q_x = \frac{m_x \omega_{ax}}{c_x}, Q_y = \frac{m_y \omega_{ay}}{c_y}\) as the drive and sense modes’ resonant angular frequencies and quality factors, usually let \(\omega_{ay} = \omega_{ax}\) in order to achieve the largest amplitude of the drive mode, and assuming \(m_y = m_p\), then \(x\) and \(y\) can be written as:

\[
\begin{aligned}
x &= A_x \sin(\omega_d t - \frac{\pi}{2}) = A_x \frac{Q_x}{m_x} \sin(\omega_d t - \frac{\pi}{2}) \\
y &= A_y \sin(\omega_d t - \varphi)
\end{aligned}
\]
Figure 5. Schematic of the periphery circuit and signal

In the drive loop, the drive frame displacement $x(t)$ is detected by the drive sense combs and then linearly transformed into the voltage signal $V_{ad}$ by the X/V convertor, and then the $V_{ad}$ is obtained once the $V_{ad}$ is amplified. $V_{ad}$’s phase is delayed 90º to satisfy the phase requirements of the AC drive signal $V_{dAC} = V_{dAC} \sin(\omega_{d}t)$. After that, $V_{dAC}$ is picked up using a full-wave rectifier and a low pass filter, and, later, $V_{dAC}$ is compared with the reference voltage $V_{r}$. Next, the integrator controller generates the $V_{dI}$ utilizing the output of the comparator, and the drive AC signal $V_{AC}$ is generated by $V_{dI}$ modulated with $V_{dAC}$. Finally, the drive DC signal $V_{DC}$ superposing $V_{AC}$ forms the force that stimulates the drive mode. In order to describe the drive loop’s workings more clearly, the signal in the drive loop imitates the gyroscope drive mode from power-on to steady state and there is an initiating process in the loop. This paper employs the averaging method to analyse the drive loop’s working steady state to find the determinant elements of the drive frame’s amplitude.

The sense circuit is an open-loop and it employs the same interface as the drive circuit. The output signal of the amplifier $V_{s}$ is demodulated with $V_{dAC}$ to generate $V_{m}$. After passing through a low pass filter, $V_{m}$ is superposed by the bias compensation circuit (module “B”) and then produces the final signal $V_{o}$. The sense loop’s signal describes the response under the drive loop’s steady state and has a constant angular rate signal input.

2.2 MEMS gyroscope’s periphery circuit

As shown in Figure 5, the drive circuit is controlled by an AGC closed-loop with self-oscillation technology which can make the drive mode vibrate with constant amplitude at its resonant frequency (Cui et al. [21]). The sense circuit detects the displacement of the sense mode and processes the Coriolis signal.

The gyroscopes’ silicon architecture is fixed in a vacuum ceramic package, which is fixed on the PCB board with a periphery circuit. The metal shell protects the gyroscope.
and restraints electromagnetic interference, just as shown in Figure 6. The power supply of gyroscope circuit is ±8V DC, and the output signal is collected by an Agilent digit multimeter, and the sample rate is 1 point per second. The turntable inside the temperature controlled chamber (TCC) provides different angular rate input under different temperatures. In order to isolate the interrupt signal, the metal case, turntable surface and TCC are connected together.

Power on and cooling the TCC down to -40°C then keep -40°C 1 hour to make sure the gyroscope’s inside temperature is steady. After that, collect 1000 points of bias and calculate an average value to represent the bias value under this temperature. Then, test the scale factor and raise the temperature up by 20°C. Repeat the process above to get the bias and scale factor’s values at -20°C, 0°C, 20°C, 40°C and 60°C.Bias and scale factor’s temperature curves are analysed to investigate the compensation method and evaluate the compensation effect.

Power on and cooling the TCC down to -40°C then keep -40°C 1 hour to make sure the gyroscope’s inside temperature is steady. After that, collect 1000 points of bias and calculate an average value to represent the bias value under this temperature. Then, test the scale factor and raise the temperature up by 20°C. Repeat the process above to get the bias and scale factor’s values at -20°C, 0°C, 20°C, 40°C and 60°C. Bias and scale factor’s temperature curves are analysed to investigate the compensation method and evaluate the compensation effect.

\[ F_d = 4 \frac{\partial C_d}{\partial x} V_{DC} V_{AC} \]  

(7)

where, \( C_d \) is the capacitance formed by the drive combs on one side. Use inputs (7) to (1), expand \( V_{AC} \) and combine with Figure 5, then get:

\[ \ddot{x} + \frac{\omega_n^2}{Q_s} \dot{x} + \omega_n^2 x = 4 \frac{\partial C_d}{\partial x} V_{DC} V_{AC} (t) K_{XYD} K_{DI} R \dot{x} \]  

(8)

\[ \dot{V}_{d}(t) = G(V_f - V_{d_{AC}}) \]  

(9)

\[ \dot{V}_{d_{AC}} = |K_{XYD} K_{DI} R| \alpha_d - \dot{\lambda}_d V_{d_{AC}}(t) \]  

(10)

Assuming the drive displacement is:

\[ x(t) = a(t) \cos(\omega_n t + \phi(t)) \]  

(11)

where \( a(t) \) and \( \phi(t) \) are the amplitude and phase of the drive frame’s displacement, then its speed can be expressed as:

\[ \dot{x} = \dot{a} \cos(\omega_n t + \phi(t)) - a(t) \sin(\omega_n t + \phi(t)) (\omega_n + \dot{\phi}) \]  

(12)

According to the averaging method, there is another equation:

\[ \dot{a} \cos(\omega_n t + \phi(t)) - a(t) \dot{\phi} \sin(\omega_n t + \phi(t)) \equiv 0 \]  

(13)

then (12) can be simplified as:

\[ \dot{x} = -a(t) \omega_n \sin(\omega_n t + \phi(t)) \]  

(14)

Furthermore, the acceleration of the drive frame is:

\[ \ddot{x} = -\ddot{a} \omega_n \sin(\omega_n t + \phi(t)) - a(t) \omega_n \cos(\omega_n t + \phi(t)) (\omega_n + \dot{\phi}) \]  

(15)

By substituting (11), (14) and (15) into (8) then the following can be obtained:

\[ -\left( (\omega_n - \frac{\omega_n^2}{Q_s}) \sin(\omega_n t + \phi) \right) - a(t) \omega_n \cos(\omega_n t + \phi) \]  

(16)

Input (13) to (16) and separate the parameters, we then get:

\[ \dot{a} = -\frac{\omega_n}{Q_s} \sin^2(\omega_n t + \phi) - 4 \frac{\partial C_d}{\partial x} V_{DC} K_{XYD} K_{DI} R \sin^2(\omega_n t + \phi) \]  

(17)

\[ \dot{\phi} = -\frac{\omega_n}{2Q_s} \sin(2\omega_n t + 2\phi) - 2 \frac{\partial C_d}{\partial x} V_{DC} K_{XYD} K_{DI} R \sin(2\omega_n t + 2\phi) \]  

(18)
By substituting (14) to (10) and applying the average method, considering the average value in one period \(T = \frac{2\pi}{\omega_n x}\) of (9), (10), (17) and (18):

\[
\dot{V}_d (t) = \frac{1}{T} \int_0^T G(V_f - V_{dAC}) dt
\]  

(19)

\[
\ddot{V}_{dAC} = \frac{1}{T^2} \int_0^T \left[ K_{SVD} K_{d} R(t_\omega) \sin(\omega_n t + \phi(t)) \right] dt
\]  

(20)

\[
\ddot{a} = \frac{1}{T^2} \int_0^T \left[ -\alpha \omega_n \frac{\partial}{\partial x} + 4 \frac{\partial C}{\partial x} V_{SVD} K_{SVD} R(t) \sin(\omega_n t + \phi) \right] dt
\]  

(21)

\[
\ddot{\phi} = \frac{1}{T^2} \int_0^T \left[ -\alpha \omega_n \frac{\partial}{\partial x} + 2 \frac{\partial C}{\partial x} V_{SVD} K_{SVD} R(t) \sin(2\omega_n t + 2\phi) \right] dt
\]  

(22)

then:

\[
\dot{V}_{dAC} = G(V_f - \ddot{V}_{dAC})
\]  

(23)

\[
\ddot{V}_{dAC} = \frac{2}{\pi} \pi_{\omega_n} K_{d} R(t_\omega) \left| K_{SVD} \right| - \lambda \dot{V}_{dAC}
\]  

(24)

\[
\ddot{a} = \frac{\pi}{2} \omega_n \frac{\partial}{\partial x} + 4 \frac{\partial C}{\partial x} V_{SVD} K_{SVD} R(t) \dot{V}_{dAC}
\]  

(25)

\[
\ddot{\phi} = 0
\]  

(26)

Let the right side of (23), (24), (25) be equal to zero, then get:

\[
\ddot{V}_{dAC} = V_f
\]  

(27)

\[
\ddot{a} = \frac{\pi \left| K_{SVD} \right|}{2 \omega_n} \dot{V}_{dAC}
\]  

(28)

\[
\ddot{\phi} = 0
\]  

(29)

So, the drive close system only has this one stable status. Under these conditions, the drive frame’s vibrating amplitude \(a\) is governed by the drive mode’s resonant frequency, reference voltage and drive loop gain.

The sense circuit is an open loop as shown in Figure 5, the signal after the demodulator can be expressed as:

\[
V_n = y(t) K_{SVD} V_{dAC}(t)
\]  

(30)

Substituting (2), (3), (5) and \(V_{dAC}\), it can then be expressed:

\[
V_n = \frac{A \Omega K_{SVD} K_{d} V_{dAC} \left[ \cos(2\omega_n t - \phi) - \cos \phi \right]}{2 \omega_n - \omega_f}
\]  

(31)

After the LPF the high frequency’s component is eliminated, before the compensation the output signal is:

\[
V_o = \frac{A \Omega K_{SVD} K_{d} V_{dAC} \cos \phi}{2 \omega_n - \omega_f}
\]  

(32)

So, the scale factor can be expressed as:

\[
K_s = \frac{\pi \phi V_{dAC} K_{SVD} \cos \phi}{4 \omega_n K_{d} R(\omega_n - \omega_f)}
\]  

(33)

When the drive circuit works at its stable status, substituting \(AX\) with \(\ddot{a}\) in (28) and letting \(V_{dAC}=V_f\) \(\omega_n=\omega_f\) then:

\[
K_s = \frac{\pi \phi V_{dAC} K_{SVD} \cos \phi}{4 \omega_n K_{d} R(\omega_n - \omega_f)}
\]  

(34)

From (34), it is obvious that the scale factor has a positive coefficient relationship with \(V_f\), \(\cos(\phi)\), and sense loop gain; a negative coefficient with \(\omega_n\) drive loop gain and the difference in the two modes’ frequencies \(\Delta\omega=\omega_n - \omega_f\). \(\Delta\omega\) and \(\omega_n\) change very little (several Hz) during -40°C~60°C, so according to (3), \(\cos(\phi)\) can be considered as being constant when the temperature changes. Otherwise, \(\Delta\omega\) and \(\omega_n\) are difficult to change once they are fabricated, but the scale factor can be adjusted easily using the periphery circuit by varying the drive amplitude and the sense loop gain.

This paper would like to clarify that two specimens with the same structure and circuit are tested in this paper’s work, and the results are reproducible. So, in order to make the paper simpler to read and understand, this paper only displays the tests curves of specimen A (quite similar to that of specimen B), and the test results of specimen B are listed at the end of the paper.

![Figure 7. Scale factor’s temperature curve before compensation](image-url)
Just like the process steps mentioned in Figure 1, the scale factor values under different temperatures are tested before the compensation and these are shown in Figure 7. Three repetitive experiments prove its repeatability and the average value is calculated using the data which indicates that the scale factor’s tempco is 693ppm/°C. The red line is a linear fit (using the least square method) of the average data, which is considered to be the scale factor’s temperature drift line:

\[
K_s = -0.00705(\text{mV}/\text{s}/°C) \times t(°C) + 10.29345(\text{mV}/\text{s})
\]  

(35)

3.1 Compensation using drive loop gain

As investigated in the above section, the scale factor is inversely proportional to the drive loop’s pre-amplifier gain \(K_{DA}\) (compensation point “SA” in Figure 5). Meanwhile, equation (35) shows that the scale factor has a negative tempco with \(K_{DA}\), so \(K_{DA}\) should have the same tempco in order to decline the scale factor’s variation. The circuit diagram of this modular is shown in Figure 8, and this circuit can achieve a high gain with an accurate phase (Graeme [22]).

The parameter names of the pre-amplifier in drive loop gain do not have dotted boxes above the components (\(R_{St}\) does not exist in the drive loop, so it is considered as a short cut here) and the transfer function of this modular can be expressed as:

\[
K_{psa} = \frac{V_{sd}}{V_{sd}} = \frac{(R_{D2} + R_{S1})R_{D3}}{R_{D3}(R_{D3} + R_{D4} + R_{St})}
\]

(36)

where, \(R_{Dk}\) is the thermal resistance mentioned in (6); \(R_{D2}-R_{D4}\) are low tempco constant resistances. Configure the appropriate values of the resistances so as to make \(K_{DA}\) have the same tempco as the scale factor and the temperature test results are shown in Figure 9. The scale factor’s tempco is reduced to 257ppm/°C and three repetitive tests are utilized to verify the reliability of this compensation method.

3.2 Compensation through sense loop gain

The sense loop gain \(K_{SA}\) is proved to influence the scale factor in (34), so the tempco of the scale factor can be declined by changing \(K_{SA}\)’s value. Since the scale factor has a negative tempco, \(K_{DA}\) is expected to have a positive one to compensate it. The circuit in this modular (“SB” in Figure 5) is the same as the pre-amplifier in the drive circuit as shown in Figure 8. The parameter names have dotted boxes under the components (\(R_{Dt}\) is considered short cut here). So, \(K_{SA}\) is governed by the equation:

![Figure 8. Pre-amplifier circuit schematic](image)

![Figure 9. Scale factor curve with drive loop gain compensation](image)
where,  are precise resistances with a constant value and tiny tempco;  is the thermal resistance satisfied with equation (6). Adjust the parameters so that  has an appropriate tempco to compensate the scale factor in Figure 7. Temperature experiments are done and shown in Figure 8, the average data is calculated (the red dot line), which shows that the scale factor tempco is reduced to 250ppm/°C.

The results of these two compensation methods are nearly the same, and this paper chooses the sense loop gain compensation method (SB) to continue the bias compensation.

4. Bias compensation

Bias is the gyroscope’s output signal, which is picked up by the navigation system directly, so bias stability and temperature character are some of the most crucial parameters for a gyroscope. According to the process flow in Figure 1, the temperature curve of the bias is obtained after scale factor compensation, described in Figure 11.

The least square method is utilized to evaluate the relationship between temperature and bias (before bias compensation, the modular “B” does not exist):

\[ V_o = V_{so} = K_{so}t + b_{so} \]  \hspace{1cm} (38)

where,  is the output bias;  is the output of the low pass filter;  =5.801mV/°C and  =751.19mV are the  ’s tempco and 0°C value. Bias compensation is based on a summator with a thermal resister in the output module of the sense circuit (compensation point B in Figure 5), the schematic is illustrated in Figure 12.

This module contains two parts: one is for temperature compensation and the other part corrects the bias’ average value. The final output signal  is governed by:

\[ V_o = -R_{bt}\left(\frac{V_{cc}}{R_S} + \frac{V_D}{R_{st}}\right) + \frac{V_{so}}{R_{st}} \]  \hspace{1cm} (39)

where,  and  are the reference voltage;  is a thermal resistance described in (6);  and  are constant value resistors. The parameters are calculated to compensate  and  in (38) and the test results are depicted in Figure 13. The variation in the whole temperature range is reduced from 29.58 mV(103.89º/h/°C) to 2.80 mV(9.70 º/h/°C), three repetitive tests curves prove this compensation method’s repeatability is exceedingly good (the red dot line is their average value).
### Table 1. Contrast of before and after compensation

| Specimen  | Before compensation | After compensation | Improvement*** | 20°C value | Max error | Tempco** | 20°C value | Max error | Tempco** |
|-----------|---------------------|--------------------|---------------|------------|-----------|----------|------------|-----------|----------|
|           | SA                  | SB                 |               | Ks         | (mV)      | (ppm/°C) | Vb         | (mV)      | (%/h/°C) |
| Specimen A|                     |                    |               | 10.25      | 0.71      | 693      | 726.03     | 29.58     | 103.89   |
|           | SA                  | SB                 |               | 8.93       | 10.39     | 0.23     | 0.26       | 257       | 250      | 4.98     | 2.80     | 9.70 |
|           | Improvement***      |                    |               | -          | -         | 67.6%    | 63.3%      | 62.9%     | 63.9%    | -        | 90.5%    | 90.7% |
| Specimen B|                     |                    |               | 13.11      | 0.84      | 640      | 47.96      | 36.71     | 100.78   |
|           | SA                  | SB                 |               | 11.87      | 13.2      | 0.43     | 0.34       | 362       | 257      | 3.94     | 4.40     | 12     |
|           | Improvement***      |                    |               | -          | -         | 48.8%    | 59.5%      | 43.4%     | 59.8%    | -        | 88.0%    | 88.0% |

Work in reference [14]

| Specimen B | Before compensation | After compensation | Improvement | 20°C value | Max error | Tempco** | 20°C value | Max error | Tempco** |
|            |                     |                    |             | 9.77/s     | 6.7/s     | 241.2****| 9.77/s     | 6.7/s     | 241.2****|
|            | SA                  | SB                 |             | 0.102/s    | 0.977/s   | 35.172***| 0.102/s    | 0.977/s   | 35.172***|

Improvement = (1-(value after compensation)/(value before compensation))*100%

Max error in references [18] = |max (zero bias) - min (zero bias)| in Table2, i.e. 12.43-5.73 (%) and 10.369-(-0.608) (%) (°/h/°C)

Tempco in references [18] = (Max error)*(3600s/h)/(temperature range)

### 5. Conclusion

This article investigates and summarizes the MEMS gyroroscope temperature compensation methods proposed in the existing literature and presents a novel idea for compensating the scale factor and bias’s tempco utilizing a thermal resistor based on the periphery analogue circuit over the range of -40°C to 60°C. The gyroroscope’s architecture is a symmetric dual proof mass with fully-decoupled, periphery circuits containing a drive self-oscillating closed-loop and sense open-loop. The scale factor is compensated in the first stage, a kind of high precision thermal resistor $R_t$ is configured in a drive and a sense loop gain to calibrate the scale factor’s tempco. The second stage is to employ a summator to compensate the bias’s tempco and value. In order to verify the repeatability of the method, three identical experiments are arranged for every stage. Two specimens are tested and the results verify the compensation methods have excellent reproducibility. The crucial result of before and after compensation is contrasted in Table 1, the 20°C $K_s$ value (which is considered as the reference point for calculating the data) only changes 1.3% (0.69%), and the tempco is reduced from 693ppm/°C (640 ppm/°C) to 250ppm/°C (257ppm/°C) and improves by 63.9% (59.8%). The bias value is eliminated quite a lot: from 726.03mV (47.96mV) down to 4.98mV (3.94mV) and its tempco decreases from 103.89º/h/°C (100.78º/h/°C) to 9.70º/h/°C (12º/h/°C). The compensation results are superior to 35.7 º/h/°C and 35.172 º/h/°C in references [14] and [18]. With this method, the volume and power consumption of the circuit stays almost the same, meanwhile the compensation circuit is simple and is highly reliable (depending on the high capability thermal resistance).

### 6. Acknowledgments

The gyroscope used in this paper was designed by the Key Laboratory of Micro Inertial Instruments and Advanced Navigation Technology of the Ministry of Education in Southeast University, the authors in this paper would like to acknowledge the support of the National Natural Science Foundation of China under Grant No.60974116, No.61101021 and No.61104217.

### 7. References

[1] Fei JT, Ding HF, et al. (2012) Robust adaptive neural sliding mode approach for tracking control of a MEMS triaxial gyroscope. International Journal of Advanced Robotic Systems. 24:1-8.

[2] Fei JT, Ding HF (2010) System dynamics and adaptive control for MEMS gyroscope sensor. International Journal of Advanced Robotic Systems. 4:77-82.

[3] Leland RP (2005) Mechanical-Thermal Noise in MEMS Gyroscopes. IEEE Sensors Journal. 3:493-500.

[4] Ferguson MI, Keymeulen D, Peay C, Yee K, Li DL (2005) Effect of temperature on MEMS vibratory rate gyroscope. Aerospace Conference IEEE. pp1-6

[5] Patel C, McCluskey P, Lemus D (2010) Performance and reliability of MEMS gyroscopes at high
temperature. IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems. pp1-5

[6] Sun F, Guo QF, Ge YS, Li JS (2006) Research on thermal characteristic in slow-small temperature changing for MEMS linear vibration gyroscope. Proceedings of the 2006 IEEE International Conference on Mechatronics and Automation, Luoyang, China. pp475-479

[7] Liu GJ, Wang A, Jiang T, Jiao JW, Jang JB (2008) Effects of environmental temperature on the performance of a micromachined gyroscope. Microsyst Technol. 14:199-204.

[8] Joo, JW, Choa, SH (2007) Deformation behavior of MEMS gyroscope sensor package subjected to temperature change. IEEE Transactions on Components and Packaging Technologies. 30:346-354.

[9] Trusov AA, Schofield AR, Shkel AM (2008) Performance characterization of a new temperature-robust gain-bandwidth improved MEMS gyroscope operated in air. Sensors and Actuators A. 155:16–22.

[10] Ho GK, Pourkamali S (2010) Micromechanical IBARs: tunable high-Q resonators for temperature-compensated reference oscillators. Journal of Microelectromechanical Systems. 19:503-515.

[11] Tsai NC, Sue CY (2009) Compensation to imperfect fabrication and asymmetry of micro-gyroscopes by using disturbance estimator. Microsyst Technol. 15:1803-1814.

[12] Cao HL, Li HS (2013) Investigation of a vacuum packaged MEMS gyroscope architecture's temperature robustness. International Journal of Applied Electromagnetics and Mechanics. 41:495-506.

[13] Hou ZQ, Xiao DB, Wu XZ, Su JB, Chen ZH, Zhan X (2012) Effect of die attachment on key dynamical parameters of micromachined gyroscopes. Microsyst Technol. 18:507-513.

[14] Zhu XH, Chu HJ, Shi Q, Qiu AP, Su Y (2009) Experimental study of compensation for the effect of temperature on a silicon micromachined gyroscope. Proceedings of the Institution of Mechanical Engineers, Part N: Journal of Nanoengineering and Nanosystems. 222:49-55.

[15] Zhang YS, Wang SW (2011) Modeling and error compensation of MEMS gyroscope dynamic output data within the whole temperature range. Advanced Materials Research. 311-313:768-771.

[16] Zhang ZX, Feng LH, Sun YN (2011) Temperature Modeling and Compensation of Double H Quartz Tuning Fork Gyroscope. Procedia Engineering. 15:752-756.

[17] Fang JC, Li JL (2009) Integrated model and compensation of thermal errors of silicon microelectromechanical gyroscope. IEEE Transactions on Instrumentation and Measurement. 58:2923-2930.

[18] Xia DZ, Chen SL, Wang SR, Li HS (2009) Microgyroscope temperature effects and compensation-control methods. Sensors. 9:8349-8376.

[19] Lee SH, Cho J, Lee SW, Zaman MF, Ayazi F, Najafi K (2009) A low-power oven-controlled vacuum package technology for high-performance MEMS. Proc. of IEEE MEMS, 2009. pp753-756.

[20] Fei JT, Juan WR, Li TH (2011) An adaptive fuzzy control approach for the robust tracking of a MEMS gyroscope sensor. International Journal of Advanced Robotic Systems. 8:125-133.

[21] Cui J, Chi XZ, Ding HT, Lin LT, Yang ZC, Tan GZ (2009) Transient response and stability of the AGC-PI closed-loop controlled MEMS vibratory gyroscopes. Journal of Micromechanics and Microengineering. 19:1-17.

[22] Graeme J (1993) Composite Amplifier Hikes Precision and Speed [J]. Electronic Design Analog Applications Issue. June 24, 30-38.