Error Analysis and Compensation Research of Scale Factor for MEMS Gyroscope

LIU Chang-zheng[1, 2], WANG Xiang-jun[1, 2], TANG Qi-jian[1, 2]

1. State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, Tianjin, 300072, P.R. China
2. MOEMS Education Ministry Key Laboratory, Tianjin University, Tianjin, 300072, P.R. China

ABSTRACT

In dynamic condition, scale factor has been one of the main errors for MEMS (micro electromechanical system) gyroscopes. This paper, based on one kind of gyroscope in the airborne optoelectronic pod, studies the variation law of the scale factor and its compensation under different environment temperature and operating speed, and then puts forward to the method of combination of ambient temperature and actual angular velocity when compensating the MEMS gyroscope's scale factor error. Test result demonstrates that the scale factor error can be effectively suppressed, and compared with compensation method only based on temperature or angular velocity separately, this new method is easy practical and presents better performance.

Keywords: MEMS gyroscope; scale factor; nonlinear error; thermal characteristic; error compensation

1. INTRODUCTION

In the control system of airborne optoelectronic reconnaissance device, which aims to realize the targets' capture, tracking and measurement, high tracking accuracy of the optical axis of optoelectronic sensors facing towards the target is an essential. To meet the demand of servo tracing carriers' vibration isolation, gyroscope, along with accelerometer as the space velocity measuring device is usually applied, with its advantages of small size, light weight, low power consumption and price [2].

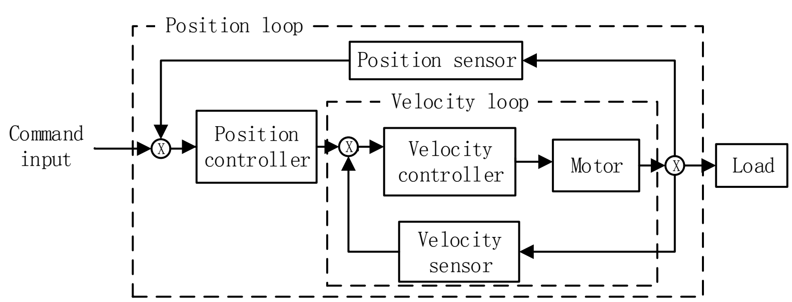

Figure .1 Typical Servo Control System

Fig. 1 Demonstrates a typical servo control system, sometimes the current loop is needed for better performance [1].

Further Author Information: (Send Correspondence to Liu Chang-zheng)
Liu Chang-zheng, E-mail: lczxhzjy@hotmail.com, Telephone: +81 02227403395
Wang Xiang-jun, E-mail: xdocuxjw@vip.163.com
Tang Qi-jian, E-mail: ytqjtang@163.com

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MEMS gyroscope senses the carrier's vibration in the inertial space and outputs a voltage which is proportional to the angular velocity, after which the controller will produce a trimming moment equal to the disturbance in the opposite direction to keep the light of sight (LOS) stable, the feedback control of the velocity loop can also increase the bandwidth and the quickness of the position loop, which improves tracking performance in return [3].

In practical application, such a system is strongly subject to the working environment and device performance as the noise and drift of gyroscope reduce the signal resolution, especially when the input signal is very tiny, leading to the migration of the LOS and losing the target and fuzzy images. Therefore it is of vital importance to work out a proper testing and compensation method of MEMS gyroscope scale factor.

Since silicon gyroscope has low precision and serious nonlinear error, it is essential to perform the research and calibration of the gyroscope, the accurate collection of relevant data and error compensation included, to improve the inertial device's performance [4].

As temperature and scale factor nonlinear error are the main error sources of MEMS gyroscope, this study aims to put forward a new compensation model to improve the gyroscope's measurement accuracy and reduce the scale factor error.

2. SCALE FACTOR ERROR ANALYSIS

2.1 Temperature Characteristic Analysis

Typically, a MEMS gyroscope outputs as below [5-7],

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} k_x \\ k_y \\ k_z \end{bmatrix} * \Omega + \begin{bmatrix} V_{x_0} \\ V_{y_0} \\ V_{z_0} \end{bmatrix} + \begin{bmatrix} \xi_x \\ \xi_y \\ \xi_z \end{bmatrix} \tag{1}$$

Where k_i is the scale factor, Ω a certain angular velocity along the z axis, V_{i_0} the zero bias and ξ_i the noise drift of each axis. In this case, we consider that V_{i_0} is well compensated and the noise drift has been filtered to tolerance range before by hardware design， so we mainly focus on the scale factor, and the ξ should be canceled accordingly.

As a kind of thermo-sensitive material, silicon gyroscope's performance characteristics are highly dependent on the temperature variation [6 , 7].Fig. 2 and Fig. 3 show the sensitivity drift over temperature variation.

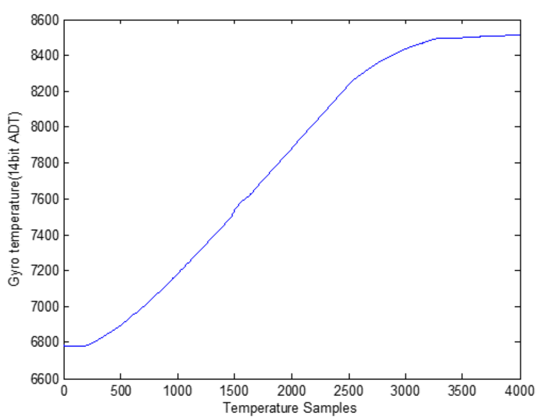


Figure .2 Temperature Drift (Actual Curve)

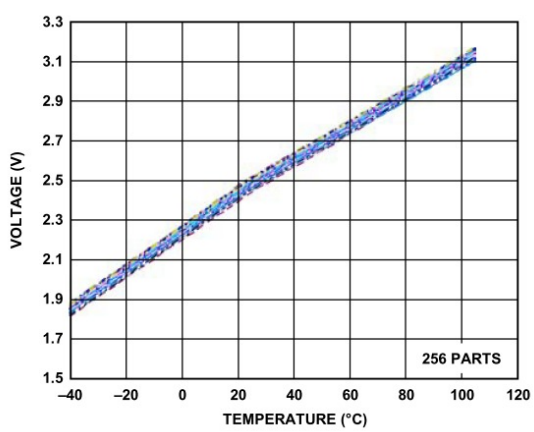


Figure .3 Gyroscope Temperature Output (Theoretical Curve)

For MEMS gyroscope, the device heating and ambient temperature change will influence the internal temperature, which leads to sensing unit distorted, internal stress and modulus changed, affecting the stiffness of elastic beams[9,10], and Q-value differs owing to the drift of the detection frequency difference[11], such factors eventually change the scale factor. Consequently, we shall no longer use the linear model to describe the influence of deformation on internal stress, considering the Green-Lagrange stress effect [9], the system stiffness has nonlinear relationship with the temperature change [12].

So we change k_i into:

$$\begin{bmatrix} k_x \\ k_y \\ k_z \end{bmatrix} = \begin{bmatrix} \lambda_{x0} & \lambda_{x1} & \lambda_{x2} \\ \lambda_{y0} & \lambda_{y1} & \lambda_{y2} \\ \lambda_{z0} & \lambda_{z1} & \lambda_{z2} \end{bmatrix} * \begin{bmatrix} 1 \\ T \\ T^2 \end{bmatrix} \tag{2}$$

Fig. 3 shows that there is good linear relationship between the gyroscope temperature output and the outside environment, so we can replace the environment temperature with the output T.

2.2 Angular Velocity Characteristic Analysis

Set U_i the supply voltage, then signals on the two drive electrodes should be $U_i(k_d \pm k_A \sin(w_d t))$, and drive moment by the electrostatic effect

$$\begin{aligned} M_1 = x\int dF_1 = \frac{1}{2}\varepsilon h_d U_i^2 (k_D + k_A \sin(w_d t))^2 \int_a^{a+l} \frac{x dx}{(z_0 + x\sin(\theta_x))^2} \\ M_2 = x\int dF_2 = \frac{1}{2}\varepsilon h_d U_i^2 (k_D - k_A \sin(w_d t))^2 \int_a^{a+l} \frac{x dx}{(z_0 + x\sin(\theta_x))^2} \end{aligned} \tag{3}$$

So the join moment is simplified as

$$M_d = M_1 - M_2 = \varepsilon \frac{A_d(2a+l)}{z_0^2} k_A k_D U_i \sin(w_d t) \tag{4}$$

Where A_d is the active area, ε the dielectric constant, a and l the distance between the x axis and driving electrode, z_0 the initial distance between the driving electrode and the inside frame, k_d the offset driving voltage coefficient, k_A the alternating driving voltage coefficient, w_d the alternating driving voltage frequency.

The inside frame and the mass block will do harmonic vibration in x axial direction:

$$\theta_x = Q_x \frac{M_d}{K_x} = Q_x \frac{M_d}{J_x \omega_x^2} \tag{5}$$

Where Q_x is the driving modal quality factor, K_x the torsional rigidity of the driving mode, w_x the natural frequency of the driving mode of the system. When z axis senses an angular velocity Ω_z, the mass will sense Coriolis force in y axis[13]

$$M_G = J_x \theta_x \Omega_z \tag{6}$$

Where J_x is the equivalent rotary inertia when mass and the inside frame rotate by the x axis, and θ_x the angular velocity when the inside frame rotates by the x axis. The vibration in the y axis will be:

$$\theta_y = \frac{M_G}{J_y S^2 + D_y S + K_y} = \Omega_Z * \frac{J_x S \theta_x}{J_y (S^2 + 2\tau\omega_y S + \omega_y^2)} \tag{7}$$

Where J_y is the equivalent rotary inertia when the system rotates by the y axis, D_y the camping coefficient and τ the damping ratio. As the asymmetric defect during the manufacture of the MEMS gyroscope exists, it will generate deviation in the J_y, Q_x and the M_d[14].So the electric capacity generated by the two sensitive pole:

$$\Delta C = f(\theta_y) = -\frac{\varepsilon h_s}{\theta_y} \ln \frac{z_0^2 - (s+b)^2 \theta_y^2}{z_0^2 - (s*\theta_y)^2} \tag{8}$$

While s and b the distance between sensitive pole and y axis and the width of the pole, h_s the active length of the sensitive pole.

Formula (6) demonstrates that ΔC and θ_y are not linear dependence strictly, so we set scale factor's expression [13]:

$$k_i(\Omega) = k_s + \sum_{j=1}^{n}(C_j\Omega^j) + \xi_k \tag{9}$$

Where k_s is the ideal scale factor of the MEMS gyroscope, ξ_k the stochastic error of the factor. To get the practical relational expression between the k_i and the actual angular velocity, we simplify the formula (9):

$$k_i(\Omega) = \sum_{j=1}^{n}(A_i\Omega^j) \tag{10}$$

Usually we make n=2, and for the specific test in this paper, the gyroscope is a z-axis MEMS gyroscope driven by the inside frame, then we get a simple expression

$$k_z(\Omega) = a_0 + a_1 * \Omega + a_2 * \Omega^2 \tag{11}$$

As with formula (3), we get

$$k_z(T) = b_0 + b_1 * T + b_2 * T^2 \tag{12}$$

Finally, we combine these two formulas together and consider both of the temperature characteristic and the angular velocity characteristic, thus

$$k_z(\Omega, T) = [1 \quad \Omega \quad \Omega]\begin{bmatrix} d_{00} & d_{01} & d_{02} \\ d_{10} & d_{11} & d_{12} \\ d_{20} & d_{21} & d_{22} \end{bmatrix}\begin{bmatrix} 1 \\ T \\ T^2 \end{bmatrix} \tag{13}$$

Throughout the demonstration, we know that the scale factor of MEMS gyroscope is highly affected by the ambient temperature and the input angular velocity. Thus the main job of this paper is to compensate the ambient temperature error and nonlinear error of the input angular velocity. Given the same temperature and different velocity, the nonlinear error of the scale factor is the main error, while temperature drift on the other way.

3. DATA ACQUISITION AND TEST

3.1Data Acquisition system

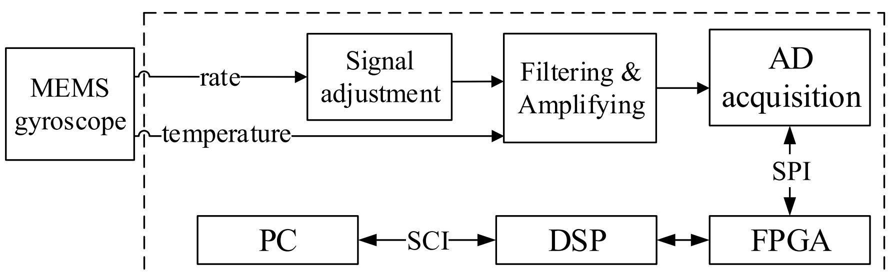


Figure .4 Schematic Diagram of the DAS

Fig. 4 shows the testing process of the data acquisition system. In the practical test, the system has two channels of gyroscope interface both of which include temperature and rate signals. After the earlier signal adjustment module and the filtering module, the signals enter the Analog-Digital acquisition module and then will be sent to the DSP from the FPGA, then the data will be sent to the PC terminal via a serial port [15].

3.2 Data Acquisition approach

The data acquisition works with two variables, the ambient temperature where the MEMS gyroscope is placed and the angular velocity. With a temperature controlling rotating platform, it is feasible to set one independent variable each time and get the signals we need. The gyroscope goes through different rates of heating up, with the temperature changing from -20℃ to 50℃, under each one the rate varies from -48°/s to +48°/s. Steps as shown below.

1) Keep the gyroscope stable for an hour after the ambient temperature has reached the set point, so that the temperature output reflect the real ambient temperature to the most degree.
2) Set the rate at -48°/s and electrify the gyroscope and data acquisition system, then collect gyroscope signals for 5 minutes. Change the rate by adding 3°/s each time, and collect the signal again.
3) When the data has been acquired, stop the rotating platform and interrupt power supply of the data acquisition

system, and stand for an hour till the chamber temperature recovers normally.

4) Reset the temperature to add 10℃ each time in step 1, then repeat 1~3 respectively.

4. DATA PROCESSING AND RESULT ANALYSIS

4.1 Temperature characteristic analysis

Fig. 3 has shown that there is good linear relationship between the gyroscope temperature output and the outside environment, we shall replace the ambient temperature with the sampled signal. Then preprocess the signal data with Kalman Filter [16, 17] before we take it into the formula. Fig. 5 shows the effect using the Kalman Filter.

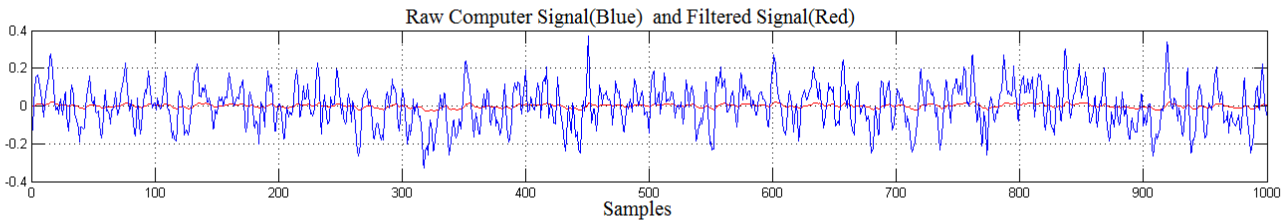


Fig 5. Signal before/after Kalman Filter

Firstly, consider the relationship between the temperature and the scale factor, change the speed of the rotating platform and send the ration signal to the PC-terminal at each temperature point, then list the scale factor and the temperature below, then the data can be analyzed by use of curve fitting method, so we get:

Forward direction:

$$k_z(T) = 24.09276 - 0.02042092381 * T + 0.00020126429 * T^2 \tag{14}$$

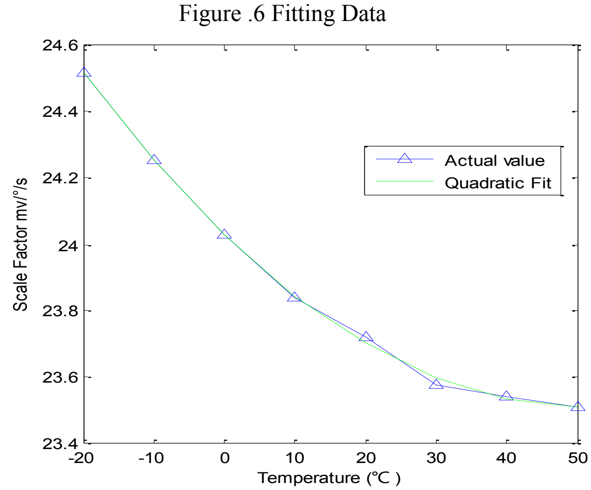
Opposite direction:

$$k_z(T) = 27.840603 - 0.00240428155 * T - 0.000096473512 * T^2 \tag{15}$$

Table 1.Scale Factor at different Temperature

temperature	forward direction	opposite direction
-20	24.5186	27.8501
-10	24.254	27.855
0	24.029011	27.835975
10	23.840285	27.821645
20	23.721757	27.737495
30	23.576835	27.688822
40	23.542188	27.589236
50	23.5118	27.4792

Figure .6 Fitting Data



Through Fig. 6, we find that it is possible to apply linear square method to reflect the relationship between the ambient temperature and the scale factor.

4.2 Angular Velocity Characteristic Analysis

Set the temperature point while collecting the output signal with the rotating platform speed varying from 3°/s to 48°/s. Meanwhile, set the signal collected at the opposition direction as control group. Table 2 lists the result of this condition.

Table2 Scale Factor at Different Speed

Sample	14bit AD data	Scale factor	Sample	14bit AD data	Scale factor
1	8504.5656	2.169180	9	10419.3976	2.577800
2	8748.6488	2.238280	10	10654.318	2.838880
3	8988.9452	2.140820	11	10887.8332	2.859560
4	9229.0532	2.019240	12	11116.1412	3.073980
5	9470.9108	2.205440	13	11344.2116	3.167700
6	9709.2588	2.293420	14	11570.0784	3.380020
7	9946.1132	2.346680	15	11793.3988	3.586440
8	10183.3408	2.351860	16	12011.9892	3.834720

The gyroscope's scale factor is not only effected by the ambient temperature but also the angular velocity, both of the formula (8), formula (9) and the experiment have put it clear. Just apply the least square fitting to these formulas as we did in section 4.1 and then we get

$$k_z(\Omega) = 2.1764379 - 0.01191166456578685 * \Omega + 0.00097452264 * \Omega^2 \tag{16}$$

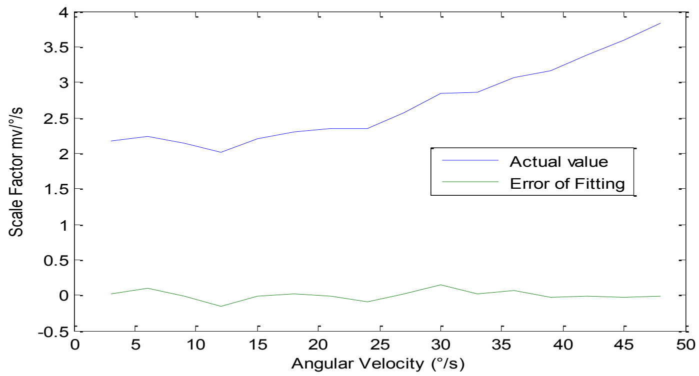


Figure .7 Scale Factor at Different Angular Velocity

4.3 Overall Consideration of Temperature and Angular Velocity Characteristic

Section 4.1 and section 4.2 has talked about the influence of ambient temperature and the angular velocity on the MEMS gyroscope scale factor separately, it is of more practical value and useful to consider the combined influences on the scale factor, so we set the temperature point of the rotating platform from 0℃ to 40℃ and the speed -48°/s to 48°/s. Take overall consideration of these two factors and we will get Fig. 8.

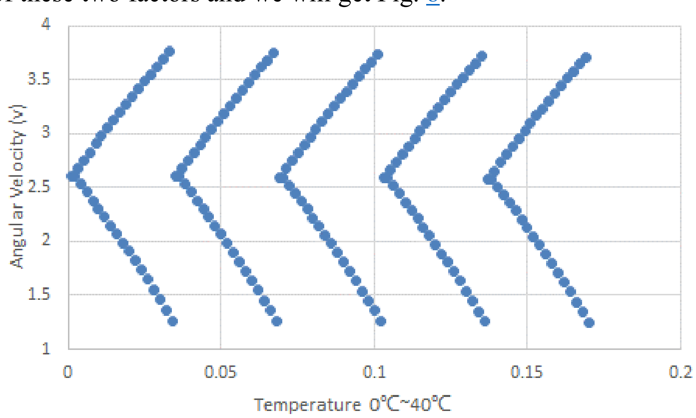


Figure .8 Signals at different Velocity and Temperature

Through Fig. 6, we find that it is possible to apply linear square method to reflect the relationship between the ambient temperature and the scale factor. And Fig. 7 shows that such method applies to the angular velocity nonlinear error too.

Then resolve the matrix in the formula (13) based on the formula (14) and formula (16), typically, formula (13) can be written as

$$k_z(\Omega, \mathrm{T}) = d_{00} + d_{01}T + d_{02}T^2 + d_{10}\Omega + d_{11}\Omega T + d_{12}\Omega T^2 + d_{20}\Omega^2 + d_{21}\Omega^2 T + d_{22}\Omega^2 T^2 \tag{17}$$

The coefficient matrix can be resolved by putting the data from the section 4.1 and section 4.2.

The theoretical coefficient of the scale factor of the MEMS gyroscope this paper uses is 20mv/°/s, for the compensation method, the relative deviation will be 0.2 taking only the ambient temperature into account, while the final relative deviation of the scale factor reaches 0.139 if we consider nonlinear error under different input angular velocity. The new mode in this paper, which combines the temperature error and velocity error to compensate the scale factor, consequently achieves better result.

5. CONCLUSION

Based on the analysis of the internal structure and the operating mechanism of the silicon MEMS gyroscope, this paper has discussed the environmental temperature error and nonlinear error separately and then mixed these two factors together and discussed the combined influence, then derived that the scale factor error of the MEMS gyroscope is dependent on the ambient temperature and input angular velocity, a new compensation model has been put forward due to this conclusion. The testing result shows that, compared with simple variable compensation method, the multivariate compensation performs better and improves the scale factor accuracy. Moreover, the final formula with only a coefficient matrix has characteristic of readily access in actual operation.

6. ACKNOWLEDGEMENTS

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