

Research on A Gyro Error Calibration Method Based on Dynamic Compensation

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Abstract: Gyroscopes in Micro-Electro-Mechanical Systems (MEMS) technology have high accuracy, convenient use, and broad application prospects. In practical applications, it is found that angular rate error is one of the main reasons that affect the output accuracy of gyroscopes. In the angular rate error calibration of MEMS gyroscopes, the method of calibrating the gyroscopes only by changing the bias and scale coefficients obtained by fitting cannot meet the angular rate error calibration of MEMS gyroscopes whose dynamic range exceeds $\pm 100^\circ/\text{s}$. Therefore, the research proposes an improved calibration method to solve the problem of angular rate error, using dynamic compensation algorithms to achieve dynamic compensation for the angular rate of MEMS gyroscopes. Experiments show that using the dynamic compensation calibration method proposed in this paper, the root mean square error of the angular rate of MEMS gyroscopes has decreased by 52.37% compared to the previous one, verifying the feasibility of this method.

Keywords: MEMS gyroscope, Angular rate error, Dynamic compensation.

1. Introduction

MEMS gyroscope is an essential inertial device in inertial navigation systems, and plays a very important role in the navigation and guidance process [1, 2]. At the same time, compared to traditional mechanical gyroscopes, MEMS gyroscopes have the advantages of small size, low cost, high reliability, and large measurement range [3, 4]. In inertial navigation system technology, the scale factor, bias, and installation errors of MEMS gyroscopes have a significant impact on the accuracy of inertial measurement units [5, 6]. At the same time, in practical applications, there is a coupling effect between various sensitive axes [7]. Especially for high-precision MEMS gyroscopes, even small errors can seriously reduce the measurement accuracy of the gyroscope [8]. Therefore, how to more accurately calibrate the angular rate error of the gyroscope has become a relatively important

research content in the field of inertial navigation system technology.

2. Error Model of Three Axis Gyroscope

In the attitude inertial measurement system, due to the deviation between the installation directions of the gyroscope in the three axes of the inertial device and the carrier attitude coordinate direction, each axis of the inertial device forms a deviation angle of different sizes. Due to the different deviation angles, the coordinate system composed of three axis inertial devices is not an orthogonal coordinate system. As shown in Fig. 1, $OX_gY_gZ_g$ is the coordinate system of a three axis MEMS gyroscope, and $OX_bY_bZ_b$ is the carrier coordinate system.

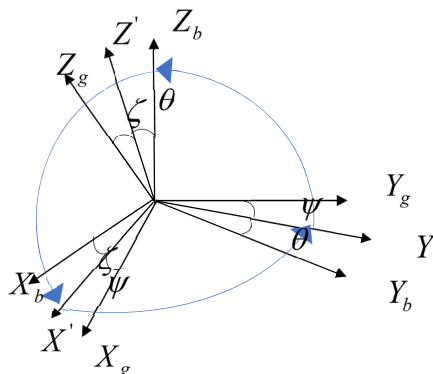


Figure 1. Three-axis MEMS gyroscope coordinate system

The relationship between them is represented by a coordinate transformation matrix [10], as shown in Equation (1).

$$C_g^b = \begin{pmatrix} \cos\psi \cos\theta & \sin\theta \sin\zeta \cos\psi + \sin\psi \cos\zeta & -\cos\psi \sin\theta \cos\zeta + \sin\psi \sin\zeta \\ -\cos\theta \sin\psi & \cos\zeta \cos\psi - \sin\zeta \sin\psi \sin\theta & \cos\psi \sin\zeta + \sin\psi \sin\theta \cos\zeta \\ \sin\theta & -\sin\zeta \cos\theta & \cos\theta \cos\zeta \end{pmatrix} \quad (1)$$

If the input angular rate of the attitude meter is ω_{ib}^b , the output of the three-axis MEMS gyroscope is as shown in Equation (2).

$$\omega_{ig}^g = C_b^g \omega_{ib}^b \quad (2)$$

At the same time, simplify the transformation matrix, as shown in Equation (3).

$$C_b^g = \begin{pmatrix} B_{xx} & B_{yx} & B_{zx} \\ B_{xy} & B_{yy} & B_{zy} \\ B_{xz} & B_{yz} & B_{zz} \end{pmatrix} \quad (3)$$

Therefore, the output of a three axis MEMS gyroscope integrated with Equations (1), (2), and (3) is shown in Equation (4).

$$\begin{pmatrix} \omega_{xg} - \omega_{x0} \\ \omega_{yg} - \omega_{y0} \\ \omega_{zg} - \omega_{z0} \end{pmatrix} = \begin{pmatrix} B_{xx} & B_{yx} & B_{zx} \\ B_{xy} & B_{yy} & B_{zy} \\ B_{xz} & B_{yz} & B_{zz} \end{pmatrix} \begin{pmatrix} \omega_{xb} \\ \omega_{yb} \\ \omega_{zb} \end{pmatrix} \quad (4)$$

Where, $\omega_{xg}, \omega_{yg}, \omega_{zg}$ is the measured value of a three axis MEMS gyroscope, $\omega_{xb}, \omega_{yb}, \omega_{zb}$ is the input angular rate of the three axis MEMS gyroscope, and $\omega_{x0}, \omega_{y0}, \omega_{z0}$ is the zero offset of the three axis MEMS gyroscope, respectively. Therefore, for the calibration of the angular rate error of MEMS gyroscopes, it is only necessary to calculate the $B_{xx}, B_{xy}, B_{xz}, B_{yx}, B_{yy}, B_{yz}, B_{zx}, B_{zy}, B_{zz}$ and the $\omega_{x0}, \omega_{y0}, \omega_{z0}$, i.e., 9 proportional coefficients and zero bias.

3. Dynamic Compensation

The linear range of a MEMS gyroscope is the range within which the gyroscope can measure the maximum and minimum angular rates, which objectively describes the gyroscope's ability to measure angular rates. The smaller the range of angular rates that can be measured, the higher the resolution of the MEMS gyroscope, but the weaker its ability to sense rates accordingly.

Therefore, in MEMS gyroscopes with a wide range of linearity and strong diagonal rate sensitivity, when calibrating angular rates that exceed $\pm 100^\circ/\text{s}$, it is not possible to rely solely on modifying the scale coefficient. Because MEMS gyroscopes are sensitive to angular velocity at this time, modifying the scale coefficient may easily cause significant changes in nearby angular velocity, and its accuracy error cannot be well controlled.

After obtaining the scale coefficient and bias of the MEMS gyroscope, dynamic error compensation is performed by fitting the angular rate input of the three-axis turntable and the actual output value of the angular rate of the gyroscope through Origin software. Segmentation is performed according to the fitting situation, and the linear relationship between the actual output value of the angular rate of each

segment of the gyroscope and the error (actual output value - input value of the three-axis turntable) is obtained in turn, As shown in Equations (5) and (6).

$$gyr_{over} = gyr_{out} - gyr_{in} \quad (5)$$

$$gyr_{over} = k \cdot gyr_{out} + b \quad (6)$$

Where, gyr_{over} is the error, gyr_{out} is the actual output value of the angular rate of the MEMS gyroscope, and gyr_{in} is the input value of the three-axis turntable.

Therefore, after obtaining the k and b in the linear relationship, the angular rate of the final output of the MEMS gyroscope can be obtained by bringing it into Equation (7).

$$G_{out} = gyr_{out} - (k \cdot gyr_{out} + b) \quad (7)$$

Where, G_{out} is the actual output value of the angular rate of the MEMS gyroscope after dynamic compensation.

4. Calibration Experiment of MEMS gyro

4.1. Attitude meter

The attitude meter integrates a 3-axis MEMS gyroscope, a 3-axis MEMS accelerometer, and a 3-axis magnetometer, as shown in Fig. 2.

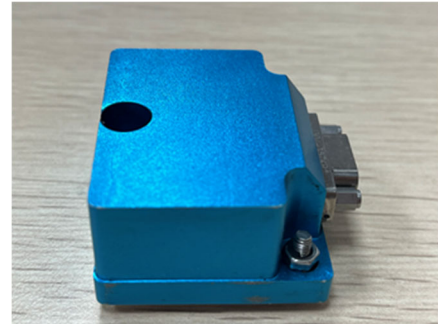


Figure 2. Attitude meter

4.2. High precision three-axis turntable

The high-precision three-axis turntable is mainly used to provide different attitudes of the attitude meter. In the rate mode, it provides the input angular velocity for the attitude meter, as shown in Fig. 3.

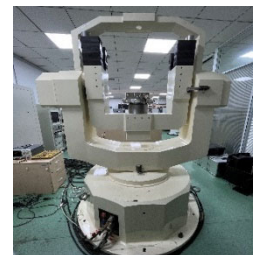


Figure 3. High precision three-axis turntable

4.3. Calibration scheme

In order to ensure the calibration effect, this paper uses a high-precision three-axis turntable to carry out the calibration experiment of MEMS gyroscope. By rotating the inner and middle rings of the three-axis turntable, the input angular rate is sequentially provided for the three-axis MEMS gyroscope. At the same time, every experiment requires reinstalling the MEMS gyroscope to ensure that the sensitive axis of the gyroscope is always perpendicular to the plane of the turntable spindle. The specific calibration process is as follows:

(1) Install the attitude meter on the turntable plane, and use the 422 interface to connect the attitude meter and the upper computer. The coordinate system of the attitude meter is shown in Fig 4.

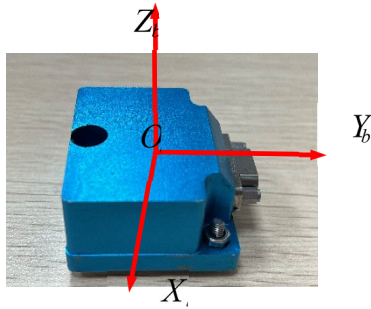


Figure 4. Attitude meter coordinate system

Note: When installing the attitude meter, make sure that the axis of the attitude meter is perpendicular to the plane of the inner ring of the turntable.

(2) Enable the three-axis turntable, set the initial positions of the inner, middle, and outer rings to 0, and then put them all in the rate mode. After checking the connection and confirming that there is no error, use a digital voltage source to power the attitude meter.

(3) Rotate the inner and middle rings in turn to provide input angular rates for the three shafts (X, Y, Z). The input angular rate gradually increases $10^\circ/s$ from $-300^\circ/s$ to $+300^\circ/s$, while collecting at least 500 rows of raw data from a three axis MEMS gyroscope after each angular rate stabilizes.

(4) Use the collected raw data to obtain the corresponding calibration coefficient of the MEMS gyroscope. Repeat step 3. Note that the range of input angular rate at this time is the maximum linear range of the MEMS gyroscope, and take the axial direction corresponding to the heading angle as an example.

4.4. Calibration coefficient calculation

First of all, use MATLAB to calculate the average value of each axis at each input angular rate based on the collected raw data of the three axis MEMS gyroscope. Using the input angular rate of the three axis turntable as the theoretical value, and the raw data of the MEMS gyroscope as the measured value, you can obtain the zero deviation of the three axis MEMS gyroscope and the proportional coefficient of the corresponding axis, as shown in Table 1.

Table 1. Calibration coefficient of three axis MEMS gyroscope

| Parameter | Value | Parameter | Value |
|---------------|----------------|-----------|--------------------|
| ω_{x0} | -0.072 113 333 | B_{yx} | -9.697 347 220e-05 |
| ω_{y0} | -0.006 933 333 | B_{yy} | 1.020 340 178 |
| ω_{z0} | 0.063 420 999 | B_{yz} | -0.000 214 016 |
| B_{xx} | 1.020 263 089 | B_{zx} | -0.000 230 130 |
| B_{xy} | 0.000 260 592 | B_{zy} | 0.000 355 058 |
| B_{xz} | 0.000 230 804 | B_{zz} | 1.020 015 376 |

The error model equation of the gyroscope is shown in Equation (8).

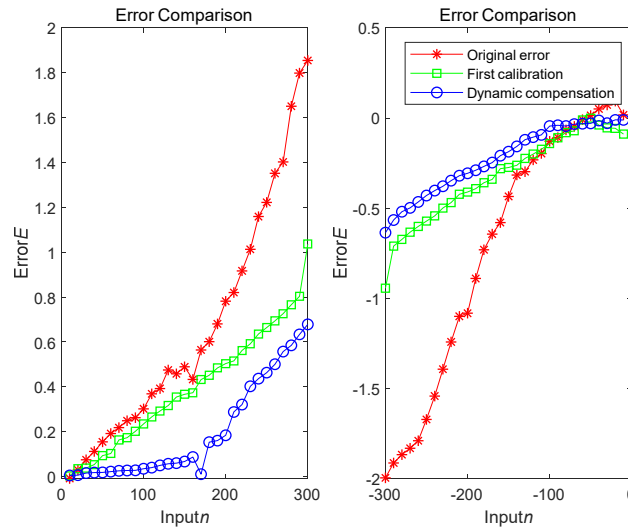
$$\begin{pmatrix} \omega_{xg} + 0.072\ 113\ 333 \\ \omega_{yg} + 0.006\ 933\ 333 \\ \omega_{zg} - 0.063\ 420\ 999 \end{pmatrix} = \begin{pmatrix} 1.020\ 263\ 089 & 0.000\ 260\ 592 & 0.000\ 230\ 804 \\ -9.697\ 347\ 220e-05 & 1.020\ 340\ 178 & -0.000\ 214\ 016 \\ -0.000\ 230\ 130 & 0.000\ 355\ 058 & 1.020\ 015\ 376 \end{pmatrix} \begin{pmatrix} \omega_{xb} \\ \omega_{yb} \\ \omega_{zb} \end{pmatrix} \quad (8)$$

Table 2 shows the segmentation of the gyro angular rate error after the first calibration and the k and b of the linear relationship between the actual output of the angular rate and the error within each segment.

Bring the sum in Table 2 into Equation (8) for dynamic compensation of gyro angular rate error. Finally, the calibration error result is shown in Figure 5.

Table 2. Segmentation of angular rate fitting

| Numble | Range (°/s) | k | b |
|--------|--------------|---------|----------|
| 1 | [210, 300] | 0.00116 | 0.18033 |
| 2 | [150, 210] | 0.00315 | -0.23781 |
| 3 | [100, 150] | 0.00210 | -0.07780 |
| 4 | [60, 100] | 0.00138 | -0.00570 |
| 5 | [-130, -50] | 0.00139 | -0.01476 |
| 6 | [-210, -130] | 0.00287 | 0.17081 |
| 7 | [-240, -210] | 0.00110 | -0.20120 |
| 8 | [-300, -240] | 0.00347 | 0.36245 |

**Figure 5.** Error Comparison

The root mean square error is shown in Table 3.

Table 3. Root mean square comparison

| Axles | Before calibration(°/s) | First calibration(°/s) | Second calibration(°/s) |
|-------|-------------------------|------------------------|-------------------------|
| Z | 0.8531 | 0.4763 | 0.2967 |

From Table 3, it can be concluded that the root mean square of the angular rate error after the first calibration is $0.2204^\circ/\text{s}$, and the root mean square of the angular rate error after the second calibration using the dynamic compensation algorithm is $0.1052^\circ/\text{s}$, which is 52.37% lower than the angular rate error after the first calibration.

5. Summary

For the calibration of MEMS gyroscopes, an improved calibration method is proposed in this paper. On the premise of using bias and scale coefficient for calibration, the calibration method of dynamic compensation of MEMS gyroscopes' angular rate is adopted, which reduces the average error value of MEMS gyroscopes in the full range linear range by less than 52.37. This provides high-precision angular rate for attitude determination and navigation, and has strong practical value.

Acknowledgment

On the occasion of completing this paper, first of all, I would like to thank my friend Huang Fuchao for his rigorous

and thoughtful scientific research spirit and optimistic and positive learning attitude, which have greatly benefited me. He is generous and benevolent in his work, rigorous and wise, and has provided us with unremitting guidance in our learning. In addition, I would like to thank all the teachers in the team for their enthusiastic guidance on the research topic. Here, I want to express my sincere respect and gratitude to you!

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