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Research on MEMS gyroscope calibration method based on Total-least squares

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Abstract

Compared with traditional gyroscopes, MEMS gyroscopes have the advantages of low power consumption, small size and easy integration. But the precision of gyroscope has great influence on its application in inertial navigation system. Therefore, analyzing and compensating various error parameters is important to improve the accuracy of gyroscope. In the article, based on the analysis of the zero drift, installation error and scale factors of gyroscope, a full parameter model of error is established. The total least square method is introduced to solve the problem of noise in both input and output observation equations in error calibration model. Finally, the effectiveness of the proposed method is verified by rate calibration experiments. Experimental results show that the absolute error of the gyroscope compensated by this method is less than 0.06999°/s, and the linearity is improved by 1-2 orders of magnitude.

Keywords

MEMS gyroscope, Total-least squares, error model, velocity calibration.

1. Introduction

Gyroscope is a key component of inertial navigation system, and its working precision directly determines the precision of inertial navigation system [1, 2]. In the inertial navigation system, the gyroscope is fixed to the carrier, and the carrier movement makes the gyroscope produce output value, and then combined with the given initial information for navigation output calculation, so as to read the attitude information of the carrier [3, 4]. However, even the gyroscope with perfect principle and structure, errors caused by various interference factors affect the working accuracy of the inertial navigation system. Therefore, improving the precision of gyroscope has important research significance for its application in inertial navigation system to measure carrier attitude.

The measurement accuracy of gyroscope is affected by its zero drift, installation error and scale factors. For these errors, the method of mathematical fitting is usually used to compensate. The gyro error parameter model is established, the original data of the gyro is calibrated with a high-precision test equipment turntable, and then the parameters in the error model are fitted through the collected data to compensate the gyroscope. With the further development of science and technology, many scholars have also studied new calibration methods. Wu Yuanxin, Pei Ling and others proposed a method to calibrate the gyroscope in a uniform magnetic field by using the magnetometer. The method used the calibrated magnetometer to calibrate the parameters of the gyroscope under sufficient rotational excitation [5]. However, the calibration process needs to be carried out in a uniform magnetic field, so the experimental conditions are difficult to satisfy. Li Wang and Tao Zhang proposed an effective calibration method for three-axis gyroscope servo motor, which does not need to use high-precision equipment in the calibration process and can shorten the calibration time [6]. Qifan Zhou and Guizhen Yu designed kalman filter to carry out calibration. Compared with the traditional method, this method only requires users to rotate manually to complete calibration [7]. To sum up, many scholars have studied error calibration methods of gyroscopes to varying degrees, and it is the main direction of gyroscope calibration in the future to seek calibration methods that are more convenient, shorter calibration time and less calculation.

In this article, the error of gyroscope is analyzed, the error model is established, and a calibration method based on Total-least squares method is proposed. This method compensates the influence of zero drift, installation error and scale factors on the gyroscope through algorithm. Finally, experiments verify the feasibility of the proposed method.

2. Calibration principle of MEMS gyroscope

2.1. Error analysis and model establishment of gyroscope

The working accuracy of strapdown inertial navigation system largely depends on the accuracy of gyroscope, which is affected by various errors. In MEMS gyroscope, its working accuracy is mainly affected by zero drift, scale factor and installation error. Therefore, the accuracy of strapdown inertial navigation system can be improved by analyzing the error source of the gyroscope, establishing the mathematical model of measurement error, and compensating the error term of MEMS gyroscope.

In the attitude measurement system, the three-axis MEMS gyroscope itself is non-orthogonal due to the production process, and the actual output coordinate system does not completely coincide with the carrier coordinate system, forming an installation error Angle, resulting in the output value of the gyroscope error. The above errors are defined as installation errors. When the MEMS gyroscope input is zero, the theoretical output is also zero, but the actual output is not zero due to the influence of the capacitive coupling error of the device processing process and the phase error generated by the interface circuit. So the actual output value of gyroscope in zero state is defined as zero deviation. In addition to installation error and zero deviation, there are scale factors which affect the output rate of gyroscope. The output value of MEMS gyroscope is obtained by dividing the actual measured value by the scale factor, so the error of the scale factor will directly lead to the deviation of the attitude measurement system. Therefore, the error model of the corrected output of the MEMS gyroscope can be established as:

$$\begin{bmatrix} W_x \\ W_y \\ W_z \end{bmatrix} = \begin{bmatrix} \omega_{x0} \\ \omega_{y0} \\ \omega_{z0} \end{bmatrix} + \begin{bmatrix} S_x & K_{yx} & K_{zx} \\ K_{xy} & S_y & K_{zy} \\ K_{xz} & K_{yz} & S_z \end{bmatrix} \bullet \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \tag{1}$$

Where W_x, W_y, W_z is the output value of MEMS gyroscope, ω_{x0}, ω_{y0}, ω_{z0} is the zero deviation of MEMS gyroscope output, S_X, S_y, S_z is the scale factor of MEMS gyroscope K_{xy}, K_{xz}, K_{yx}, K_{yz}, K_{zx}, K_{zy} is the installation error coefficient of MEMS gyroscope, ω_x, ω_y, ω_z is the actual measured value of MEMS gyroscope. It is worth noting that both the input and output of this model are speed of the turntable.

2.2. Total-least squares method

For the overdetermined matrix equation Ax=b, the idea of the ordinary least square method is that there is no probability assumption for the data vector B, but only a signal model is assumed, so it is not optimal. However, in many cases, the observed b vector will be affected by the observed noise. In order to overcome this shortcoming of the least square method, the total least square method should be introduced. The idea of the total least square method can be summarized as follows: disturbance vector and disturbance matrix are respectively used to correct the disturbance in A and B. Therefore, the total least square method is mainly to solve the following matrix equation:

$$(A+E_A)x = b+e_b \tag{2}$$

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The above equation can be written as:

$$([-b, A]+[-e, E])\begin{bmatrix}1\\x\end{bmatrix}=0 \tag{3}$$

Let B=[-b, A] and D=[-e, E], so the solution of Formula (3) can be converted to the constrained optimization problem with constraint conditions of b+e Range(A+E), i.e.

$$\min_{D,X} \| D \|_F{}^2 \tag{4}$$

$$\| D \|_F = (\sum_{i=1}^{m}\sum_{j=1}^{n} d_{ij}{}^2)^{\frac{1}{2}} = \sqrt{tr(D^H D)} \tag{5}$$

Where ||D||F is the Frobenius norm of matrix D.

The matrix B consists of two sub-matrices and is a full-rank matrix. Perform singular value decomposition on matrix B and arrange its singular value matrix diagonals in ascending order,then there is C=USV^T, where $S = dig(\sigma_1,\ldots,\sigma_n,\sigma_{n+1})$, $0<\sigma_{n+1}\ldots\le\sigma_2\le\sigma_1$ .So the overall least squares solution of the overdetermined equation Ax=b is expressed as:

$$x_{TLS} = -\frac{1}{v_{n+1,n+1}}\left[v_{1,n+1},\cdots,v_{n,n+1}\right]^T \tag{6}$$

3. Experimental method and coefficient calculation

3.1. MEMS gyroscope calibration scheme

In order to obtain the relevant error parameters proposed above, the SGT-8T three-axis electric turntable produced by Beijing Institute of Aeronautical Precision Machinery was selected as the calibration of the MEMS gyroscope. The specific rate calibration steps are as follows:

The measuring X-axis of the gyroscope is fixed horizontally on the three-axis turntable, so that the three sensitive axes of the gyroscope are parallel to the three axes of the turntable, and the upper computer is connected with the gyroscope through the communication interface RS422.

Turn on the power supply of the turntable, enable and close it and other operations, then connect the stabilized power supply to the gyroscope, and preheat for 5 minutes.

Set the inner ring of the turntable as the rate mode, and the X-axis of the gyroscope is the angular rate sensitive axis. Then set the rate of the turntable to increase from -100°/s to 100 °/s, and collect data at intervals of 10°/s. When the size of the collected file reaches 120KB, a group of data is collected.

For the data of Y-axis and Z-axis, first rotate the three-axis electric turntable to make its Y-axis and Z-axis upward. Then repeat the operation of the above step (3) to collect the output rate value of MEMS gyroscope in real time. Finally, 20 sets of data of each axis can be obtained.

3.2. Calibration experiment data processing

Based on the proposed calibration scheme, the calibration data of three groups of MEMS gyroscopes along X, Y and Z axes can be obtained, and then the installation error coefficient and zero deviation error value of the gyroscopes can be obtained by the Total-least squares method fitting. The following is an analysis and explanation.

The scale factor and installation error coefficient in the error model of MEMS gyroscope can be calculated by MATLAB programming. Taking the data collected upward on X-axis as an example, set the speed of the three-axis electric turntable from -100°/s to 100°/s three axis gyroscope data collected by averaging respectively. Then the default value for the accurate value of turntable, the turntable set a gyroscope and the output value to X, Y, Z axis of the output value fitting using least square method in MATLAB. The rotary table can be obtained with the X-axis

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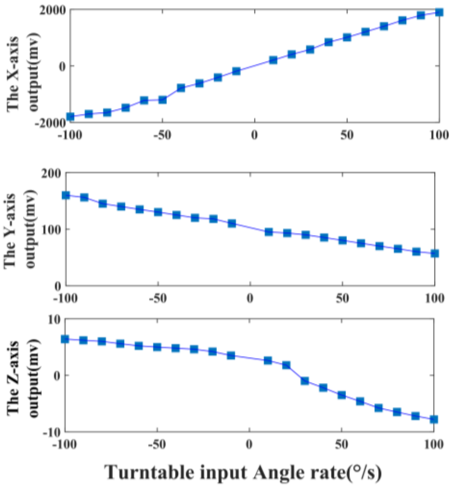
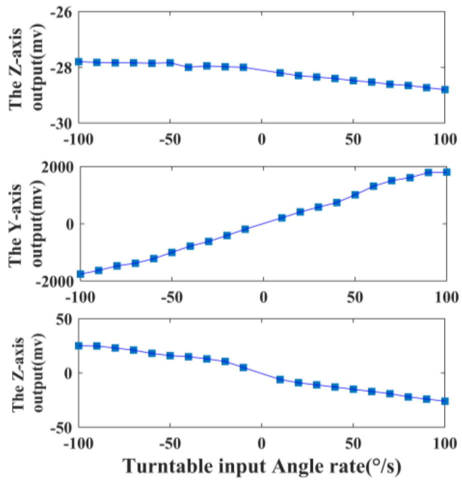
fitting the scale factor of the S_x, and the installation error values of the turntable fitting with the Y-axis and Z-axis respectively are K_{xy} and K_{xz}. Similarly, the scale factors S_z, S_y and the installation error value K_{zx}, K_{zy}, K_{yx}, K_{yz} can be obtained by fitting the gyroscope data collected on the Z and Y axes with the set value of the turntable respectively. The fitting curve is shown in Fig. 1. At the same time of each calculation, the set value of the turntable and the zero offset of the three axes of the MEMS gyroscope can also be obtained D_{xx}, D_{xy}, D_{xz}, D_{yx}, D_{yy}, D_{yz}, D_{zx}, D_{zy}, D_{zz}. Finally, the zero offset of the MEMS gyroscope can be calculated as:

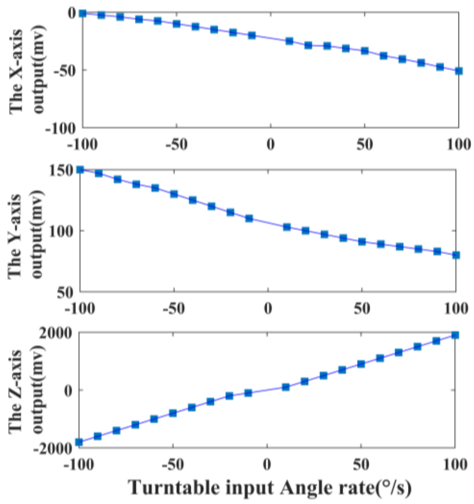
$$\begin{cases} \omega_{x0} = \left(D_{xx} + D_{yx} + D_{zx}\right)/3 \\ \omega_{y0} = \left(D_{xy} + D_{yy} + D_{zy}\right)/3 \\ \omega_{z0} = \left(D_{xz} + D_{yz} + D_{zz}\right)/3 \end{cases} \tag{7}$$



(a) X-axis measurement and fitted curve



(b) Y-axis measurement and fitted curve



(c) Z-axis measurement and fitted curve

Fig. 1 Three-axis MEMS gyroscope measurement value and fitting curve

The calibration coefficient of MEMS gyroscope is obtained by taking the set value of the three-axis electric turntable as the reference value of data fitting:

Table 1: Three-axis MEMS gyroscope calibration coefficients

Axial	Zero drift (mv)	Scale factor
X	-22.67454166	$S_x = 0.05628079$

		$K_{xy} = 0.00046929$
		$K_{xz} = 0.00022129$
Y	100.7170000	K_{yx}=1.0794006e-05
		$S_y = 0.02025715$
		$K_{yz} = 0.00027298$
Z	-44.60041666	$K_{zx} = 0.00071179$
		$K_{zy} = 0.00037781$
		$S_z = 0.05610513$

According to the error parameters in Table 1, the mathematical model of the MEMS gyroscope output of the DSP-based SINS gyroscope can be written as

$$\begin{pmatrix} \omega_{x0} \\ \omega_{y0} \\ \omega_{z0} \end{pmatrix} = \begin{pmatrix} 0.05628079 & 1.0794006\text{e-}05 & 0.00071179 \\ 0.00046929 & 0.02025715 & 0.00037781 \\ 0.00022129 & 0.00027298 & 0.05610513 \end{pmatrix}^{-1} \begin{pmatrix} \omega_{x0} + 22.67454166 \\ \omega_{y0} - 100.7170000 \\ \omega_{z0} + 44.60041666 \end{pmatrix} \tag{8}$$

The measured data within the z-axis range from -100 °/s to 100°/s of the MEMS gyroscope before calibration were substituted into Eq. (8) to obtain the calibrated values. The z-axis data of calibrated and uncalibrated three-axis MEMS gyroscope are shown in Table 2. As can be seen from Table 2, when the angular rate ranges from -100°/s to 100 °/s, the absolute value of MEMS gyroscope z-axis data error increases with the increase of the angular rate, and the installation error reaches the maximum at 100°/s. The absolute value of the maximum error of the z-axis data of the uncalibrated MEMS gyroscope is 1.06861°/s, and the absolute value of the maximum error after calibration is less than 0.06999°/s, which improves the measurement accuracy of the MEMS gyroscope by 1-2 orders of magnitude.

Table 2: Comparison of MEMS gyroscope Z-axis data before and after calibration

Input angular rate (°/s)	Unscaled value（°/s）	Calibration value（°/s）	uncalibrated error（°/s）	Error after calibration（°/s）
-100	-99.1279	-100.061	0.8721	-0.061
-80	-79.2965	-80.036	0.7035	-0.036
-60	-59.4981	-60.0445	0.5019	-0.0445
-40	-39.6638	-40.0168	0.3362	-0.0168
-20	-19.8331	-19.9926	0.1669	0.0074
-10	-9.95125	-10.0146	0.04875	-0.0146
10	9.881944	10.01199	-0.11806	0.01199
20	19.78514	20.01185	-0.21486	0.01185
40	39.56361	39.98323	-0.43639	-0.01677
60	59.35486	59.96746	-0.64514	-0.03254
80	79.15556	79.96118	-0.84444	-0.03882
100	98.93139	99.93001	-1.06861	-0.06999

In order to verify the experimental effect, the calculated error coefficients were put into the gyroscope, and the z-axis was selected to conduct the calibration experiment again. The results of the experiment are shown in Fig. 2 and Fig. 3. They are the comparison of the angular rates

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of the X-axis and Y-axis before and after calibration when the turntable speed is set to 10°/s. It can be seen from the comparison figure that the speed accuracy of z-axis is improved by 0.15°/s after error compensation compared with that before compensation, while the absolute value of installation error of Z-axis and Y-axis is less than 0.25 °/s. In general, the angular rate accuracy of gyroscope is improved obviously after compensating the zero drift, installation error and scale factor error.

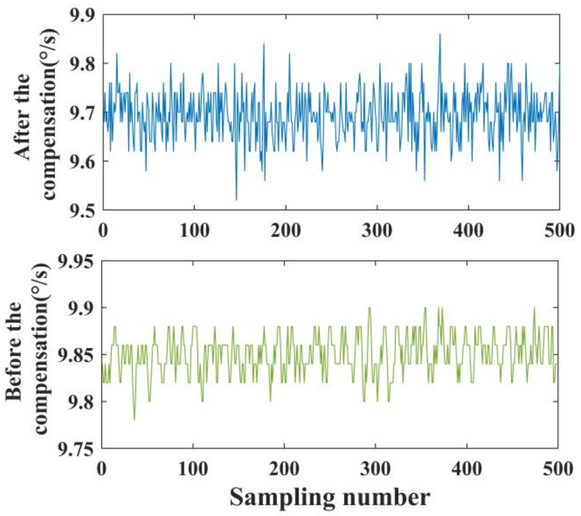

Fig. 2 X-axis calibration before and after comparison

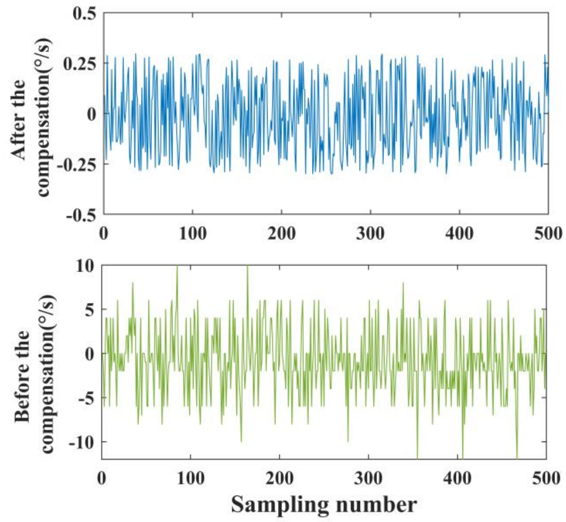

Fig. 3 Y-axis calibration before and after comparison

4. Conclusion

In this paper, the rate calibration method of MEMS gyroscope based on the Total-least squares method proposed can calibrate the zero drift, scale factor and installation error of the gyroscope in the strapdown inertial navigation system. The correctness and effectiveness of the compensation method are verified by calibration experiments. From the perspective of engineering application, the rate calibration can be carried out as long as the mathematical model of MEMS gyroscope is established accurately. This method is simple in principle, easy to implement, and has high precision.

References

[1] Liu Z, Wang L, Li K, et al. Analysis and improvement of attitude output accuracy in tri-axis rotational inertial navigation system[J]. IEEE Sensors Journal, 2020, 99(21): 1-3.

[2] Thapa K. Using Precision Current Sensing to Optimize System Performance[J]. Elektor electronics worldwide, 2019, 41(09): 56-58.

[3] Park K, Choi S, Chae H, et al. An energy-efficient multimode multichannel gas-sensor system with learning-based optimization and self-calibration schemes[J]. IEEE Transactions on Industrial Electronics, 2019, 67(3): 2402-2410.

[4] Clark J, Self-calibration and performance control of MEMS with applications for IoT[J]. Sensors, 2018, 18(12): 4411.

[5] Wu Y, and Pei L, Gyroscope Calibration via Magnetometer[J]. IEEE Sensors Journal, 2017, 17(16): 5269-5275.

[6] L. Wang, T. Zhang, L. Ye, J. J. Li and S. W. Su. An Efficient Calibration Method for Triaxial Gyroscope[J]. IEEE Sensors Journal, 2021, 21(18): 19896-19903.

[7] Zhou, Qifan and Yu, Guizhen and Li, Huazhi and Zhang. A Novel MEMS Gyroscope In-Self Calibration Approach[J]. Sensors, 2020, 20(18): 5430.