Research on temperature error compensation method of vehicle-mounted laser gyro SINS

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Abstract. In order to solve the problem that the measurement accuracy of vehicle-mounted laser gyro strapdown inertial navigation system (SINS) is affected by the temperature change, a temperature error compensation method which can adapt to the full temperature environment is proposed. Based on the phenomenon that the temperature of the inertial sensor is still rising when the temperature of the temperature control box is kept, a continuous temperature change experiment is designed. Then, Pearson correlation analysis of the output of laser gyro and quartz flexible accelerometer with temperature, temperature rate and temperature gradient has been carried out. Based on that, the temperature error models of gyro and accelerometer are constructed, and the temperature compensation method based on polynomial model is proposed. The results show that this method could compensate the temperature error of the laser gyro and the quartz flexible accelerometer effectively, and the zero-bias stability of them are both improved, especially the zero-bias stability of the accelerometer is improved by at least one order of magnitude, the accuracy of inertial measurement in full temperature environment is improved effectively.

1. Introduction

SINS needs to obtain the initial attitude information through initial alignment before navigation calculation. The accuracy and speed of initial alignment directly affect the following navigation accuracy and the mobile ability of vehicle platform. Laser gyro SINS has become a popular strapdown inertial navigation system in high precision inertial navigation application because of its stable performance, strong anti-jamming ability, high precision, high reliability and long life[1]. But the laser gyro and the quartz flexible accelerometer in the system are easily affected by the temperature change in the measurement, and the temperature error exists. If the error can not be compensated in time, it will cause the system output error to increase gradually, that ultimately leads to inaccurate information. Therefore, for laser gyro SINS, the temperature error must be compensated in order to achieve high precision initial alignment in the full temperature environment (-40℃~60℃).

The temperature error compensation of laser gyro SINS has been widely studied, including the temperature error compensation of laser gyro and quartz flexible accelerometer. In the aspect of temperature compensation, it can be compensated by means of hardware manufacture, temperature control and software. The hardware compensation method is mainly in the manufacture craft, through the reasonable design structure layout, the choice suitable part material and the component shape causes the sensor's thermal distortion to compensate each other in the interior, in order to ensure that the temperature changes in the case of parameter performance[2]. But this hardware compensation method is difficult and costly to implement. The temperature control method needs to install temperature control
equipment, which increases the volume, cost and power consumption of the system[3]. The method of software compensation is to establish the temperature error model and to compensate the temperature error in real time, a large number of studies show that this method is effective, convenient, flexible, economical and practical. The real-time compensation of laser gyro and accelerometer is realized by 3-order spline interpolation in [4], which improves the measurement accuracy and calibration stability of inertial sensor. Based on the thermal design of the four-frequency differential laser gyro, the temperature error is effectively compensated by mathematical compensation model in [5], in the temperature range of -40°C~60°C, the standard deviation is 0.013/(°·h). According to the control characteristics of the frequency stabilization system of the prismatic laser Gyro, the digital circuit technology is used to realize the temperature subsection control in [6]. The temperature error compensation method of the accelerometer based on the differential measurement of specific force is put forward by using the temperature control box without turntable to test the inertial navigation system in [7], the temperature error model can be established in the full temperature range and under the condition of fast changing temperature.

If the temperature error of gyro and accelerometer can be compensated effectively, the output precision of inertial measurement unit (IMU) will be improved, then the initial alignment accuracy and the subsequent navigation accuracy will also be improved. Therefore, this paper focuses on the study of temperature error compensation of laser gyro and quartz flexible accelerometer for laser gyro SINS, and puts forward a method of temperature error compensation for full temperature environment.

2. Mechanism of temperature error

2.1. Mechanism of temperature error in laser gyro

The laser gyro is affected by temperature mainly from two aspects. One is the heat generated by the gyro itself when it works. Another is the change in ambient temperature. The material inside the gyro will undergo thermal deformation when the temperature changes. The length of the resonator, the refractive index of the medium, the flow state of the gas, the internal temperature field and the area of the closed optical path will all change with the temperature, so it has an effect on the zero deviation, scale factor and so on, and causes the measurement error[8]. In view of the scale factor error caused by the temperature change, the low expansion coefficient material is used as the cavity, and the stability of the scale factor is kept within a certain range of temperature change by the length control device, which can control the scale factor at an acceptable level, therefore, the effect of temperature is ignored in this paper.

2.2. Mechanism of temperature error in quartz flexible accelerometer

When the ambient temperature changes in the full temperature range, the output of the quartz flexible accelerometer will be greatly influenced, and the temperature drift will be induced. Quartz flexible accelerometer is affected by temperature mainly from three aspects[9].

1) When the temperature increases, the torquer coil will become larger and the magnetic flux will increase, which will lead to the non-linear error of zero deflection.

2) The thermal unbalance of the accelerometer will cause the small deformation of the arm, which will cause the zero shift and the change of the bias of the signal sensor.

3) The temperature gradient inside the shell will cause the change of air viscosity, and then cause the change of bias.

3. Construction of temperature error model

3.1. Temperature experiment

In order to analyze the output characteristic of SINS under the circumstance of temperature change, firstly, the SINS is placed in the temperature control box to control the temperature change, and the temperature test is carried out. In the experiment design, the common practice is to carry out the constant temperature test at several temperature points first, and then do the variable temperature experiment
again. However, in the course of the experiment, it was found that the temperature of the inertial sensor would keep rising after the inertial sensor was powered on. Even if the temperature control box was set to a constant temperature, the temperature of the internal inertial sensor was also rising, and it was difficult to maintain a constant temperature. Based on this situation, the continuous slow temperature rise test under the control of the temperature control box is carried out in this paper.

First, set the temperature of the temperature control box to -40°C and keep it warm for four hours, then power up the system and control the temperature control box to slowly warm up to 50°C. The sampling frequency is 200Hz, including gyro output, accelerometer output, and temperature data. In order to reduce the high frequency noise and better reflect the inertial sensor output with the temperature change trend. The output of the gyro and the accelerometer are smoothed for 100 seconds. The smoothed output is shown in figure 1 and figure 2, where Tem represents the temperature in degrees Celsius(℃), X、Y、Z represents the inertial sensor in each axial direction respectively, Bias represents the output bias of inertial sensor in pulses/seconds (p/s).

![Figure 1 Gyro output curve](image1.png)

![Figure 2 Accelerometer output curve](image2.png)
It can be seen that the temperature change has an important effect on the output of the gyro, and the effect is more complex, and the output change trend is uncertain. Therefore, it is necessary to further analyze the influence of temperature gradient and other relevant factors before the modeling of gyro temperature error, so as to construct accurate temperature error model. From the output curve of the accelerometer, it can be seen that the temperature has an obvious effect on the output of the accelerometer, and the output instability increases. But compared to gyroscopes, accelerometers are more sensitive to temperature.

3.2. Correlation Analysis

Set temperature gradient \( \Delta T = (T_1 - T_0)/\Delta t \), where \( T_0 \) is the current time temperature and \( T_1 \) is the next time temperature. \( T \Delta T \) represents the coupling cross term of temperature and temperature gradient. The temperature change rate \( dT/dt \) is obtained by the derivation of the temperature data after smoothing fitting. Pearson correlation coefficient \( r \) is calculated to measure the correlation between gyro output bias and some factors. The formula is as follows

\[
\begin{align*}
    r &= \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \\
    \bar{x} &= \frac{1}{n} \sum_{i=1}^{n} x_i, \\
    \bar{y} &= \frac{1}{n} \sum_{i=1}^{n} y_i.
\end{align*}
\]

Where, \( x_i \) is a sequence of variables, \( y_i \) is another sequence of variables. \( \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \), \( \bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \).

The closer \( r \) is to 1 or -1, the stronger the correlation is, and the closer \( r \) is to 0, the weaker the correlation is.

Here are the conclusions of the correlation analysis.

1) The output bias of X-axis gyro and Z-axis gyro is correlated with temperature, temperature rate and cross term of temperature and temperature gradient, and the correlation degree is significant, and the correlation between temperature gradient and output bias of Z-axis gyro is also relatively weak. The correlation between output bias of Y-axis gyro and temperature, temperature gradient and cross term of temperature and temperature gradient is significant, but the correlation between output bias of Y-axis gyro and temperature rate is weak.

2) The correlation between the output bias of three axial accelerometers and the cross terms of temperature and temperature gradient is significant, but the correlation with temperature rate and temperature gradient is weak.

To sum up, in order to improve the accuracy of gyro temperature error model, temperature, temperature gradient, cross term of temperature and temperature gradient and temperature rate are introduced into the model as modeling parameters. The cross terms of temperature, temperature and temperature gradient are selected as the model parameters in the establishment of the accelerometer temperature model.

3.3. Modeling of temperature error

Considering both the compensation effect and the higher order of the model, the more computation is needed, the highest order of the temperature term in the polynomial model of laser gyro is determined to be the third order. Then the temperature error model of laser gyro is
\[ B_g = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 \Delta T + a_5 T \Delta T + a_6 \frac{dT}{dt} \]  

(2)

Where, \( B_g \) is the output bias of gyro, \( a_i \) is the fitting coefficient.

The temperature error model of accelerometer is

\[ B_a = b_0 + b_1 T + b_2 T^2 + b_3 T^3 + b_4 T \Delta T \]  

(3)

Where, \( B_a \) is the output bias of accelerometer, \( b_i \) is the fitting coefficient.

The fitting coefficients of the models of the laser gyro and the quartz flexible accelerometer are obtained by least square fitting, as shown in table 1 and table 2.

| Laser gyro | Coefficients of the model |
|------------|---------------------------|
|            | \( a_0 \) | \( a_1 \) | \( a_2 \) | \( a_3 \) | \( a_4 \) | \( a_5 \) | \( a_6 \) |
| X          | -14.22 | -1.82e-04 | -1.21e-05 | -9.91e-08 | 2.17 | 0.12 | 0.0072 |
| Y          | -0.39 | 0.0012 | 2.09e-06 | -6.90e-07 | 4.50 | 0.05 | 0.0084 |
| Z          | -11.74 | 8.62e-05 | 2.32e-06 | -1.66e-08 | -0.02 | 8.76e-05 | -8.95e-05 |

| Quartz flexible accelerometer | Coefficients of the model |
|--------------------------------|---------------------------|
|                                | \( b_0 \) | \( b_1 \) | \( b_2 \) | \( b_3 \) | \( b_4 \) |
| X                              | -63.61 | -0.012 | -0.002 | 1.56e-05 | 4.09 |
| Y                              | -1.04 | 0.074 | -2.08e-04 | -6.18e-07 | -2.18 |
| Z                              | -4.12e+03 | 0.063 | -0.002 | 1.02e-05 | -1.16 |

4. Temperature error compensation

The gyro polynomial temperature error model and the accelerometer polynomial temperature error model are used to compensate the measured data, the gyro output bias and accelerometer output bias before and after compensation are shown in figure 3 and figure 4, respectively. The blue dotted line represents the output bias of the inertial sensor before compensation, and the red solid line is the output bias of the inertial sensor after compensation.
Figure 3 Gyro output curve before and after temperature error compensation

Figure 4 Accelerometer output curve before and after temperature error compensation

From the curve change before and after compensation, it can be seen that the temperature error compensation effect of inertial sensor is remarkable. After compensation, the trend term of the gyro and accelerometer changing with the temperature is eliminated, and the output of the gyro and the accelerometer is basically horizontal. Especially for accelerometers, the comparison of output bias before and after temperature error compensation is very obvious, which also reflects the rationality of the temperature error model.

Then the zero-bias stability before and after compensation is calculated according to the standard deviation of 1 $\sigma$, as shown in table 3.
Table 3  Zero-bias stability of inertial sensor before and after temperature compensation

| Inertial sensor          | Before compensation | After compensation |
|-------------------------|---------------------|--------------------|
| Laser gyro              |                     |                    |
| X                       | 0.0097 °/h          | 0.0073 °/h         |
| Y                       | 0.0160 °/h          | 0.0076 °/h         |
| Z                       | 0.0081 °/h          | 0.0073 °/h         |
| Quartz flexible         |                     |                    |
| accelerometer           |                     |                    |
| X                       | 0.0022 g            | 0.0005 g           |
| Y                       | 0.0036 g            | 0.0002 g           |
| Z                       | 0.0028 g            | 0.000087 g         |

It can be seen that the zero-bias stability of the gyro and the accelerometer is improved after the temperature error compensation, and the zero-bias stability of the accelerometer is improved by at least one order of magnitude. The bias stability of laser gyro is also improved by temperature compensation, but the compensation accuracy is relatively low. The reason is that the influence of the temperature is relatively small, and the output of the laser gyro is nonlinear. For Laser gyro, polynomial method has some limitations, which can be further studied.

5. Conclusion

Aiming at the problem that the measuring accuracy of laser gyro and quartz flexible accelerometer in laser gyro SINS is easily affected by the temperature change, the mechanism of the temperature effect of the laser gyro and the quartz flexible accelerometer is analyzed firstly in this paper, and then the correlation of the measured data is analyzed through the temperature experiment, then the temperature error models of gyro and accelerometer are established, and the temperature error compensation method based on polynomial model is proposed. The compensation results show that the method can compensate the temperature error of the laser gyro and the quartz flexible accelerometer, especially the zero-bias stability of the accelerometer is improved remarkably. The zero-bias stability of laser gyro has been improved to some extent. Next, further research can be carried out to improve the accuracy of the compensation.

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