Research on Temperature Modeling of Strapdown Inertial Navigation System

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Abstract. Strapdown inertial navigation system with laser gyro has been deployed in space tracking ship and compared with the conventional platform inertial navigation system, it has substantial advantage in performance, accuracy and stabilization. Environmental and internal temperature affects the gyro, accelerometer, electrical circuits and mechanical structure significantly but the existing temperature compensation model is not accurate enough especially when there is a big temperature change.

1. Introduction
The application field of Strapdown Inertial Navigation System (SINS), used for navigation and stabilization, is now changed from airplane to naval ships, tactical missile, terrestrial positioning and orientation systems[1]. With the mature of technology, the application of ship-based RLG SINS has been developed very fast and becomes more and more important nowadays[2].

The influence of the temperature in inertial navigation system has two aspects: temperature change on inertial device and temperature field. In mechanically dithered SINS, while used in actual environment, the temperature variation of surroundings and heating in operative system itself will bring about changes in temperature of laser gyroscope and accelerometer themselves as well as relevant electric circles, which will finally cause variation of zero offset and scale factor of laser gyroscope and accelerometer. The calibration value is different, so that the system needs more time to finish initial alignment[3]. Laser gyro and quartz flexible accelerometer are the core of the system, and are also the temperature sensitive device, which is one of the most important factors to determine the accuracy, reliability and stability of the system.

In practical applications, the temperature model is not so precise when the temperature field changes radically; it cannot completely remove the measurement error. Considering that, we should analyze the measurement model and calculation model, conclude the characteristics of some inertial element parameter, and find out an optimization method for temperature model.

2. Analysis of Temperature Characteristic

2.1. Temperature characteristics of laser gyro
In a certain range of temperature and accuracy, it can be considered that the laser gyro is not affected by temperature, but the effect of temperature must be considered when the temperature is high or the accuracy requirement is high. Temperature in SINS will influence the data accuracy and perform in the following aspects: temperature field, gas fluent field, physical characteristics and geometrical features.
The relationship between the temperature and the output of a certain type of laser gyro is investigated. The results are shown in Figure 1. It is shown that the influence of temperature on the test accuracy is not negligible.

\[ \text{Figure 1. The output of a laser gyro and temperature change curve chart.} \]

\[ \text{2.2. Accelerometer temperature characteristic} \]

The accelerometer is the key device of the strapdown inertial measurement device based on Newton's theory of inertia, which has the characteristics of analog input, high performance and high accuracy. It can be used to measure the carrier's line acceleration, and then through the two points to get the trajectory of the carrier (the carrier's speed and distance), combined with gyroscope information, access to the carrier's full information\(^4\).

During the working process of the accelerometer, there are two main reasons resulting in changes of temperature: one is self heating; one is the environmental temperature change.

The relationship between the output and the temperature change of a certain type of accelerometer is investigated. The results are shown in Figure 2. Temperature variation has a huge affection in accelerometer’s output, its temperature characteristic also influence the initial alignment and course accuracy of SINS greatly.
3. Temperature model

3.1. Establishment of zero temperature model

Through the analysis of temperature characteristics, the influence of thermal environment on the accuracy of the system is mainly derived from the temperature error caused by the inertial sensor and its propagation in the system, which can make the parameters of the laser gyro and accelerometer significantly changed, and the accuracy of the output data is significantly affected. According to the experimental analysis of the thermal environment, the scaling factor of laser gyro and accelerometer is smaller, and the main factor is the zero deviation of the gyroscope and accelerometer. It is also a hot spot of the current research to establish the temperature model of laser gyro zero bias, and the method of the software to compensate the economic and practical. In this paper, the improvement of the temperature model of the laser gyro is studied, and the improvement of the temperature model of the accelerometer is proposed.

The temperature of zero bias is mainly reflected by the temperature change, temperature change rate, temperature gradient and so on. Zero bias temperature error compensation model can be expressed as:

$$Bias = B_0 + \varphi(T) + v(T) + \delta(\Delta T)$$  \hspace{1cm} (1)

$B_0$: Constant value part of gyro’s zero offset

$\varphi(T)$: Influence to gyro’s zero offset due to temperature variation

$v(T)$: Influence to gyro’s zero offset due to temperature change rate

$\delta(\Delta T)$: Influence to gyro’s zero offset due to temperature gradient

When environmental temperature changes slowly and the temperature gradient is stable, the effect of temperature variation on the zero deviation of the gyroscope is considered. The static temperature model of zero bias is established by polynomial fitting method. The formula (1) can be simplified as:

$$Bias = a_0 + a_1T + a_2T^2 + \ldots + a_nT^n$$  \hspace{1cm} (2)
According to formula (2) design temperature test, the zero deviation value at different temperatures
was obtained, and the static temperature model was established:

1. In the temperature range \([T_{\text{min}}, T_{\text{max}}]\), every temperature \(\Delta T\) select a temperature point, measure the
gyro bias output, and then calculate the temperature of gyro output as the average value of the temperature
of the gyro bias.
2. Solve the model coefficients \(a_0, a_1, a_2\ldots\). In the case of different temperature points, the model
coefficients are determined by polynomial fitting.
3. Determine the number of polynomial \(m\), achievement through regression coefficient of significant
test. The actual number of polynomials used are two, three, four polynomial, and can be determined
according to the accuracy of compensation.

3.2. Improvement of temperature compensation model

In the use of the zero bias temperature model based on zero bias and temperature, the model has some
limitations, and the compensation precision of the model can decrease or even diverge with the change of
environment temperature. The survey ship equipment of strapdown inertial navigation system is of high
accuracy, influence of temperature proposed higher requirements, especially the wide temperature range
high accuracy requirements, with the expansion of the scope of application, application environment
complex, need to study is of higher temperature compensation model.

Temperature variation and temperature change rate are both considered in temperature model(3); also
have improved the static model and added first order term of temperature change rate.

\[
\varepsilon = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 \frac{dT}{dt}
\]  

(3)

The forecast model(4) contains cross term and temperature change rate term, it has built a functional
relationship of zero offset with the following factors: temperature, high order term of temperature change
rate and its cross term\(^\text{[6]}\).

\[
\varepsilon = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 (\frac{dT}{dt}) + a_5 \frac{dT}{dt}^2
\]

\[
+ a_6 (\frac{dT}{dt})^3 + a_7 T (\frac{dT}{dt}) + a_8 T^2 \frac{dT}{dt} + a_9 T^3 \frac{dT}{dt}^2
\]  

(4)

Therefore, we can take further consideration to build a temperature model (5) by using present data and
historical moment temperature sequence.

\[
\varepsilon = a_0 + \sum_{i=1}^{m} a_i T_{t-(i-1)}
\]  

(5)

\(\varepsilon\), \(T_t\): gyroscope zero offset and measure value of temperature on the N sampling
\(T_{t-(i-1)}\): measure value of temperature on the \([t-(i-1)]\) sampling
\(a_0, a_i\): the coefficient of temperature compensation model
\(m\): Total number used in this model, including present and historical temperature points \(1 \leq i \leq m\)

In order to verify the effect of the temperature models (5) as mentioned above, temperature experiment
has been designed.

The result of compensation in model(1) indicates a relatively large residual; this model shows a low
accuracy in temperature compensation in condition of fast temperature change rate. To a certain extent,
Model (3) and (4) contain temperature change rate term, which enhanced their compensation ability in a
fast temperature change rate. Both of them can well compensate the phase difference between gyro’s
output and temperature, much better than model (1). Model(5) is a time series model and has the same
accuracy as model(3) when the temperature change rate changes fast. Model(3), model(4) and model(5)
have the same compensation accuracy which is superior to model(1); improvement of temperature model
in this passage is proved to be effect.
4. Temperature experiment

To verify the effect of four kinds of temperature model, a temperature test is designed. The system is placed in the temperature box, temperature change is set as shown in figure 3. The temperature change rate is $13^\circ C/h$. The temperature range is $30^\circ C$ ~ $60^\circ C$. Keep temperature for 2 hours at the temperature boundary. Obtain the temperature model coefficient.

![Figure 3. High and low temperature experiment.](image)

Modeling results of the model (2):

$$
\varepsilon = -7.1510 + 3.0739 \times 10^{-4} T + 3.5414 \times 10^{-6} T^2 - 5.5958 \times 10^{-8} T^3
$$

Modeling results of the model (3):

$$
\varepsilon = -7.1518 + 2.7846 \times 10^{-4} T + 2.6327 \times 10^{-6} T^2 - 3.6996 \times 10^{-8} T^3 + 1.78 \frac{dT}{dt}
$$

Modeling results of the model (4):

$$
\varepsilon = -7.1521 + 2.6981 \times 10^{-4} T + 3.4340 \times 10^{-6} T^2 - 4.3623 \times 10^{-8} T^3 + 2.0341 \left( \frac{dT}{dt} \right) + 78.3937 \left( \frac{dT}{dt} \right)^2
$$

$$
-0.0252T \left( \frac{dT}{dt} \right) + 1.7346 \times 10^{-4} T^2 \left( \frac{dT}{dt} \right)
$$

Modeling results of the model (5):

$$
\varepsilon_i = a_0 + \sum_{i=1}^{m} a_i T_{r(i-1)}
$$

Considering the facts of data calculation and compensation accuracy, the model temperature point number $m=25$ is selected. Modeling results of the model (5):

$$
\begin{align*}
\varepsilon_0 &= -7.1494 \\
a_1 &= -0.0481 \\
a_2 &= -0.0307 \\
a_3 &= 0.033 \\
a_4 &= -0.0475 \\
a_5 &= 0.0409 \\
a_6 &= -0.0259 \\
a_7 &= 0.029 \\
a_8 &= -0.0082 \\
a_9 &= -0.0099 \\
a_{10} &= -0.0101 \\
a_{11} &= -0.0197 \\
a_{12} &= -0.0195 \\
a_{13} &= -0.0064 \\
a_{14} &= -0.0046 \\
a_{15} &= -0.0231 \\
a_{16} &= -0.0269 \\
a_{17} &= 0.0025 \\
a_{18} &= -0.0165 \\
a_{19} &= 0.0157 \\
a_{20} &= -0.0008 \\
a_{21} &= -0.0216 \\
a_{22} &= -0.0215 \\
a_{23} &= -0.0258 \\
a_{24} &= -0.0389 \\
a_{25} &= -0.0446
\end{align*}
$$

The output of the gyro is compensated by type (6), type (7), type (8) and (9) model. The results are shown in Figure 4.
It can be seen that in the process of the experiment, the temperature change rate is great (13 °C/hr), and the compensation results of model (6) have a large residual error, and the model has a low compensation accuracy when the temperature difference is large.

The temperature change rate are added to model (7) and model (8). In a certain extent, the compensation ability of the model is improved. The two models are better than the model (6).

Model (9) is a time series model, and the compensation precision is similar to the model (7) when the temperature change rate is great.

Model (7), (8), (9) are better than the model (6), this indicates the model proposed in the 3.2 section is effective. The specific values are shown in Table 1.

| Model(6) | Model(7) | Model(8) | Model(9) |
|----------|----------|----------|----------|
| Before compensation | 0.0115   | 0.0115   | 0.0115   | 0.0115   |
| After compensation  | 0.0067   | 0.0031   | 0.0027   | 0.0034   |

5. Conclusions

This paper analyses the temperature characteristics of CLG as well as accelerometer, proposes the improvement method for present temperature model, and verifies the compensation effect through experiments. By means of comparing, the temperature model added with time series and temperature change rate performs better than before, it shows excellent environmental suitability, also available for complex temperature conditions such as wide temperature range and fast temperature variation rate.
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