Temperature Experiment and Compensation Algorithm Design for Fiber Gyros in Rapid Startup Inertial Navigation System

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Abstract. This article describes a practical thermal experiment and compensation algorithm for fiber gyros in an inertial navigation system with a rapid startup and short time operation characteristic. Multi-position cold startup experiments at discrete temperature points is designed to fully stimulate the thermal error mode. And due to the nonlinear characteristic of the error, a piecewise spline algorithm is applied to precisely identify and build the error model. After the compensation, the gyro instability in the full temperature range is reduced from the level of 5 °/h to better than 1 °/h.

1. Introduction
The fiber-optic gyroscope and the inertial navigation system (INS) with fiber gyros have become available to the application of nearly all levels of precision, which lead the trend of inertial technology [1,2]. However, as the INS application field becomes wider and its working environment more complex, these temperature-induced errors have turned into the major barrier in further improving the system performance [3]. This point is particularly evident for the INS with fiber gyros since the fiber gyros are very sensitive to the temperature variation. And maintaining the gyro bias stable is one of the top design concerns because it is the main reason which causes the position divergence and the heading error.

In tradition, temperature control has been a tried-and-tested method to reduce these thermal errors by building a stable and uniform temperature environment for the inertial sensors [4]. But it has obvious drawbacks, such as complicated hardware, bulky volume and slow transient process. In contrast, temperature compensation is a software method which directly removes the error from the sensor output by some math operations. This seems straightforward, but its effect depends greatly on the compensation model’s accuracy. Thus, the previous research concentrates on the modification of the compensation model in order to better describe the relationship between the temperature and thermal errors [5,6]. In this context, intelligent methods are also employed to do the error modelling, such as support vector machine and neural network [7,8]. But some of these models are too complicated to run on the chip of INS and can only be applied under strict conditions. On the other hand, the experiment design is general and not targeted at the specific working environment of the INS. In this paper, we focus on both experiment and algorithm design and propose a practical and detailed method to the temperature compensation of fiber gyros in an INS with a rapid startup and short time operation characteristic.

2. Experiment design for rapid startup INS
2.1. System description and thermal environment analysis
A carefully designed experiment concerning the INS actual working environment is the prerequisite of building a high accurate and adaptive model. Thus, we first analyze the INS working condition and thermal environment. The strapdown INS is in compact volume less than 100mm and composed of three fiber gyros and three quartz accelerometers. The INS normally stays in a dormancy state. After receiving the wake-up signal, the INS will turn into the navigation mode immediately and operate only for a few minutes. It can be seen that most of the time the INS is in a shutdown mode in an approximate constant temperature environment while the system position does not change much and there is no internal heat source inside. Therefore, the system can be regarded as an isothermal object. And when the power is on, nearly all the temperature change comes from the element heating, because there is not enough time for the external heat to transfer into the INS due to the limited navigation time. For the whole process, the INS is in a constant temperature environment and the inside is isothermal with the outside before the system is powered. Then after the power is on, the INS carries out a short-time cold startup in the constant temperature environment.

2.2. Experiment design
The temperature experiment design is based on the analysis above in order to fully simulate the real environment where the INS works. The experiment contains six groups of multi-position tests at different temperature states to obtain the characteristic of the thermal drift of fiber gyros. The temperature profiles of the thermal chamber with the orientations of the INS module are shown in Figure 1. They are the combination of several repetitive cold startups and powered-offs in different time length. In Figure 1, the colored markers are used to represent different control states.

Every experiment contains six constant chamber temperature states (0, 5, 10, 20, 30, 40 ℃) (during ▲—■—● process). Given the INS normally works in the low temperature environment, the temperature points in the low temperature end have a denser distribution. At each individual temperature point, the INS will be fully warmed in the powered-off state to reach a thermal equilibrium with the chamber environment (during▲—■—● process). Then, the INS starts up and the data sampling is initiated to collect the outputs of gyros and the temperature sensor (■—● process). At 20 ℃, the INS works continuously for three hours, much longer than other points. The aim of this is to make the final temperature consistent with that during the calibration process and separate the thermal drift from the gyro output in the full temperature range. The reason why multi-position experiments are carried out is because the outputs from the same gyro in opposite directions will be used to check if the temperature error is mainly induced by the bias drift (for example, gyro X in experiment group 1 and 2) and the gyro outputs in the same direction but in different groups will be used to check the repeatability of the error (for example, gyro Z in group 1 and 2). Also the data from multiple experiments can enhance the modeling accuracy. The temperature of the chamber is controlled to change in a way from low temperature to high temperature (group 1, 3, and 5) and then reversely from high temperature to low temperature (group 2, 4 and 6). This makes it possible to run the experiments successively and the total testing time can thus be reduced. Taking X gyro as an example, the gyro output and associated temperature collected from experiment 1 to 4 is shown in Figure 2. It can be seen that an obvious gyro drift occurs when the temperature changes. The peak-to-peak value is over 15 °/h. Here, we first assume the bias instability is the main cause of the drift and this hypothesis can be verified in section 3.1.
3. Compensation algorithm design

Though the thermal bias drift of fiber gyro is has a correlation with temperature changing rate (temperature derivative) [9], it is not suitable to consider this gradient effect in the compensation model. This is because the INS only operates for a short time, but the temperature changing rate needs a long time to smooth its noise. Also, at the beginning of the cold startup, the temperature increases
relatively slow which makes the temperature rate small enough. Therefore, only absolute temperature \( T \) is considered in the model. The bias drift \( \varepsilon (T) \) is denoted by

\[
\varepsilon (T) = g(T)
\]

\( \varepsilon (T) \) is extracted from the gyro output by using the three hour data mentioned previously. It is obtained by subtracting the constant calibration value from the temperature experiment result [10]. Then, the modeling aim is to identify the error-temperature correlation function \( g \).

3.1. Data preprocessing

Since the highest resolution of the temperature sensor is 0.5°C, the sampled temperature is in a stepped form and has quantization characteristic (see Figure 2). In order to smooth the noise, for every experiment, the fluctuated temperature \( T^{\text{real}} \) within the range of 1°C i.e. \( T^{\text{real}} \in [\Delta, \Delta + 1] \) is time sequenced and averaged to obtain the averaging temperature \( \bar{T}_{\Delta}^{\text{real}} \). Here, \( \Delta = 0, 5, 15, 20, 30, 40 \) °C denotes the dataset at each temperature point. This smoothed temperature along with the averaged value of the corresponding bias error \( \bar{\varepsilon}_g(\bar{T}_{\Delta}^{\text{real}}) \) are used as the identification inputs \( \bar{\varepsilon}_g(\bar{T}_{\Delta}^{\text{real}}) \sim \bar{T}_{\Delta}^{\text{real}} \). The formula is given as

\[
\begin{align*}
\bar{T}_{\Delta}^{\text{real}} &= \text{avg}_{T^{\text{real}} \in [\Delta, \Delta + 1]} (T^{\text{real}}) \\
\bar{\varepsilon}_g(\bar{T}_{\Delta}^{\text{real}}) &= \text{avg}_{T^{\text{real}} \in [\Delta, \Delta + 1]} (\varepsilon_g(T^{\text{real}}))
\end{align*}
\]

Where, \( \Delta \) is the integer temperature within the temperature range and \( \text{avg} \) denotes the averaging operation. After the preprocessing, the bias error of X gyro and the associated temperature is shown in Figure 3. Note that the thermal error from opposite directions is almost the same (group 1 and 2). This indicates the assumption is reasonable that the temperature error is mainly induced by the bias drift. And there is a nice repeatability between the bias error and the temperature, because the error shape from the same direction is similar with each other (group 3 and 4).

![Figure 3](image_url)

**Figure 3.** Smoothed results of bias error and temperature output of X gyro and temperature sensor.

3.2. Error Modeling

The task to identify the nonlinear correlation function \( g \) is accomplished by using the piecewise spline polynomial. This method has preferred engineering advantages that its form is smooth everywhere and can be flexibly adjusted to approximate a great number of nonlinear functions. Moreover, it does not bring excessive calculation burden.
For the modeling process, the temperature domain is first divided into several subintervals. In every interval, the form of the fitting function is a low order polynomial. And the functions from adjacent intervals are connected smoothly which ensures the error model is continuous across the entire temperature range. The detailed definition of spline polynomial is described as follows:

In the temperature domain \([T_{\text{min}}, T_{\text{max}}]\) (\(T_{\text{min}}\) and \(T_{\text{max}}\) are the highest and lowest gyro temperature obtained from the experiments), given a group of junction points \(T_{\text{min}} < T_1 < T_2 < \ldots < T_p < T_{\text{max}}\), there is a piecewise polynomial \(g(T)\) which satisfies:

- In every subinterval \([T_{\text{in}}, T_i]\), \([T_i, T_j]\), ..., \([T_p, T_{\text{max}}]\), \(g(T)\) is a real coefficient polynomial with the order not greater than \(Q\).
- The derivatives of \(g(T)\) with orders from 0 to \(Q-1\) are continuous.

It has been proved that the cluster of such spline functions which satisfies the above conditions can be generated by a group of basis vectors 1, \(T\), \(T^2\), \(T^3\), \(T^4\), \(T - T_i\), \(T - T_i\), \(T - T_j\), \(T - T_j\). The subscript + for \(T\) denotes \(T = \max(0, T)\).

Thus, any \(g(T)\) can be expressed as a combination of the basis vectors with the order not greater than \(Q\).

\[
g(T) = R_g(T) + S_g(T)
\]

Polynomial \(R_g(T)\) and \(S_g(T)\) are written as

\[
\begin{align*}
R_g(T) &= \sum_{i=0}^{Q} c_i T^i \\
S_g(T) &= \sum_{j=1}^{p} h_j (T - T_j)^{Q-1}
\end{align*}
\]  

(4)

Where, \(c_i\) and \(h_j\) are the indeterminate coefficients. They can be identified by substituting \(E_g(T_{\text{max}})\) and \(T_{\text{max}} \text{mod}\) into (3).

4. Results and analysis

The data from experiment 1 to 4 is employed to build the error model and the data from experiment 5 to 6 to validate the compensation efficiency. We choose order \(Q = 3\), junctions \(T_1 = 10^\circ C\), \(T_2 = 20^\circ C\), \(T_3 = 30^\circ C\) and \(T_4 = 40^\circ C\). The compensation results are shown in Figure 4. Both the modeling groups and the verification groups are well compensated. And all the thermal drift no matter in the same direction or different directions is suppressed effectively. The standard deviations (1σ, 10s smoothing) of compensated and uncompensated gyros are listed in Table 1. The gyro stability after the compensation is better than 1 °/h.
Figure 4. Thermal compensation results in different experiment groups.

Table 1. Standard deviations of gyro outputs before and after compensation.

| Group | X gyro (°/h) before | X gyro (°/h) after | Y gyro (°/h) before | Y gyro (°/h) after | Z gyro (°/h) before | Z gyro (°/h) after |
|-------|---------------------|-------------------|---------------------|-------------------|---------------------|-------------------|
| 1     | 5.0761              | 0.7235            | 0.6662              | 0.5204            | 1.7605              | 0.5860            |
| 2     | 5.0735              | 0.6967            | 0.6436              | 0.5178            | 1.7781              | 0.5842            |
| 3     | 5.1870              | 0.6771            | 0.7661              | 0.5873            | 1.8028              | 0.5771            |
| 4     | 5.1538              | 0.7003            | 0.6537              | 0.5013            | 1.8065              | 0.5736            |
| 5     | 5.0406              | 0.7034            | 0.6119              | 0.4970            | 1.7780              | 0.5814            |
| 6     | 5.2480              | 0.7447            | 0.6443              | 0.5002            | 1.7444              | 0.5948            |

Another experiment with different temperature environment is carried out to further exam the model’s efficiency. This time, the INS cold starts up at 15, 25 and 35 °C which is different from the experiment for modeling. The real-time compensation results are shown in Figure 5. And the standard deviations are listed in Table 2. We can find that the performance of the compensated gyros is consistent with the previous results and the thermal drift has been significantly reduced.
Figure 5. Thermal compensation results in experiment with different temperature environment.

Table 2. Standard deviations of gyro outputs in experiment with different temperature environment.

| Gyro Axis | Uncompensated (°/h) | Compensated (°/h) |
|-----------|---------------------|-------------------|
| X         | 3.0787              | 0.7584            |
| Y         | 0.5338              | 0.5085            |
| Z         | 0.7260              | 0.5268            |

5. Conclusion
This paper presents a practical method to compensate the temperature error of fiber gyros in a rapid startup INS. The thermal experiment and compensation algorithm design are carefully considered and tightly integrated with the INS characteristic and the system real working environment. Verification results demonstrate that the thermal stability in the complicated environment has been considerably improved. This method can also be applied for other inertial devices or other type of sensors with similar behavior.

6. References
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