Research on Heading Sensitive Drift Behavior of Inertial Platform System under Long-term Storage Condition

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Abstract

The heading sensitive drift of inertial platform system changes with the degradation of components’ performance and the coupling characteristics under long-term storage conditions. Such heading sensitive drift is different from the drift under working conditions, and it is difficult to analyze its stability for allocating resources for the calibration and maintenance in engineering application. In this paper, firstly the theory and expression of heading sensitive drift caused by servo loop zero and structure disturbing torque was presented and derived. Secondly, the drift characteristic of influence parameters was analyzed thoroughly based on the expression, and the integrated behavioral model of heading sensitive drift under servo loop zero and disturbing torque influence was concluded. And then, the long-time drift characteristic, acceleration performance and stability of heading sensitive drift behavior were analyzed with actual storage condition profile. The results indicate that heading sensitive drift on the X, Y and Z axis has the similar long-term drift characteristics without acceleration response, which is different from the response characteristic in actual use and therefore has great significance for allocating resources for the calibration and maintenance in inertial platform system.

Key words: Long-term storage; Heading sensitive drift behavioral; Servo loop zero; Structure disturbing torque

Introduction

Heading sensitive drift mainly refers to the phenomenon of output of Gyro drifts along with the heading altitude change of inertial platform system, and its value is more than ten times or even scores of times of Gyro precision level with unpredictable drift status, which is a difficult issue for the research of inertial platform system nowadays [1-3].

The influence mechanism of heading sensitive drift is complicated and inter-correlated, and its influencing factors are generally summed up into the following four: servo loop zero and structure disturbing torque, vibration, temperature and magnetic influence. Currently, researches in this regard mainly focus on the transient response of heading sensitive drift, and compensation design for the using precision of heading sensitive drift is conducted accordingly [4-7].

For the missile inertial platform system which has the characteristic of long-term storage and one time usage, many factors including bearing stiffness changing, materials creep, lubrication damping degradation and so on have great influence on the heading sensitive drift behavior under long-term storage conditions, and as their influence mechanism is complicated and inter-correlated [8-10], it brings great difficulty for the calibration and maintenance of the inertial platform system heading sensitive drift. Therefore, the research of inertial platform system heading sensitive drift storage stability is very significant for allocating resources for the calibration and maintenance.

In the paper, the influence principle of servo loop zero and structure disturbing torque is discussed, and expression of heading sensitive drift is derived from the above influence principle theory. Secondly, the drift characteristic of parameter in the expression is analyzed by comprehensive analysis and experiment measurement, and then integrated behavioral model of heading sensitive drift under servo loop zero and disturbing torque influence is concluded. Ultimately, the long-time drift characteristic, acceleration performance and stability of heading sensitive drift behavior were analyzed with actual storage condition profile. The results indicate that heading sensitive drift on the X, Y and Z axis has the similar long-term drift characteristics without acceleration response, which is different from the response characteristic in actual use and therefore has great significance for allocating resources for the calibration and maintenance in inertial platform system.

The Principle of Heading Sensitive Drift Caused by Servo Loop Zero and Structure Disturbing Torque

Research object

Figure 1 is the frame structure of inertial platform system - the research object of this paper, which is mainly composed of azimuth ring, pitch ring, rolling ring, and pedestal.

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pitch ring, rolling ring and other connection structure, and provides the
gyros output additional angle related to the heading altitude
angle drift [12].

Drift Behavioral Model of Inertial Platform System

Engineering experience has shown that servo loop zero mainly refers
to AC interference in demodulator input terminal and input zero
of DC amplifier, both of which can be analyzed by converting into the
input of demodulator, meanwhile, the disturbing torque taking effect
on the gimbal axis mainly refers to the bearing friction torque [1,14].
Therefore, this section deeply analyzed the creep mechanism and be-
behavior characteristic of demodulator input zero and bearing friction
torque, analyzed the behavioral characteristics of model parameters in
equations (1) and (2), and then comprehensively derived the heading
sensitive drift behavioral model of inertial platform system.

Drift behavior of servo loop zero

In inertial platform system, the drift mechanism of servo loop zero
in servo loop shown in figure 4(use the pitch servo loop and rolling
servo loop for examples).

Wang Fang et al. [14] pointed out that servo loop zero will change
with temperature and u1, u, u2 mainly refer to 19.2 KHz AC interfer-
ences in demodulator input terminal and input zero of DC amplifier,
which are analog circuit parameters and their performance depends on
the creep characteristic of the resistor, the capacitor and the amplifier.
The paper analyzed the degradation features of preamplifier in servo loop by experiment, and then got the drift behavioral model of servo loop zero with the initial value $u_x = u_y = u_z = 10 mV/V = 0.01 V$ as follow:

$$u_x = u_y = u_z = 0.01 \times ((17.4132 - 1.04775 \times 10^{-4} \times t - 0.00139899 \times T)$$

$$+ 2.31568 \times 10^{-5} \times t^2 + 2.35779 \times 10^{-6} \times T^2 + 2.9888 \times 10^{-7} \times t \times T) \quad (3)$$

**Drift behavior of bearing friction torque**

Bearing friction torque means all kinds of damping torque related to bearing rotating, which not only involves bearing structure, dimensions, materials, heat treatment performance, but is also influenced by the working load, lubrication situation and environment, and all those factors interact and interfere with each other, which makes the research even more complicated [10-12].

Bearing friction torque is a hot research issue currently. Its computational method can be divided into two categories, i.e., quasi static analytical method based on Herz elastic contact theory and engineering experience formula based on dynamical friction theory [15-17]. Under the long-term storage conditions, due to factors like the combat readiness or test calibration, the bearing friction torque in certain inertial platform system is featured by dynamical friction. Therefore, it can be calculated by engineering experience formula, which means dividing the bearing friction torque into two parts according to whether it is caused by working load or not, and the expression is as follows [16]:

$$M = M_0 + M_1 = 10^{-7} f_0 (vn)^{2/3} D_0^2 + \mu f_F D_0 / 2 \quad (4)$$

Where: $M_0$ is the bearing friction torque without loads ($N\cdot mm$); $M_1$ is the bearing friction torque caused by loads ($N\cdot mm$); $f_0$ means the bushes type and lubrication type; $v$ is the lubrication coefficient of lubricant base oil under the operating temperature ($mm^2/s$); $D_0$ is the bearing's outer diameter, $d$ is the bearing's inner diameter, $D$ is the bearing's outer diameter, $\mu$ is the friction coefficient; $f_1$ is the factor reflecting the load characteristic; $\tau$ is the bearing's radial load ($N$), $F_F$ is the bearing's radial load ($N$), $F = \sqrt{F_x^2 + F_y^2 + F_z^2}$, $F_x$ is the bearing's axial load ($N$).

The parameter data in Table 1 is the roller bearing structure parameter value used in certain inertial platform system.

Under the long-term storage conditions, lubrication coefficient and friction coefficient have the creep feature, which exert a tremendous influence on the bearing friction torque.

**Creep law of lubrication coefficient:** Under the storage condition, bearing in inertial platform system cannot add any extra lubricant, but meanwhile it has to be made sure that there is no lubricant starvation or lubricant accumulation. Therefore, the creep will occur to the lubricant coefficient under the impact of factors like time or temperature during the storage, which will result in changes of the bearing friction torque.

<table>
<thead>
<tr>
<th>parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>average speed ($n$/min)</td>
<td>5</td>
</tr>
<tr>
<td>bearing's inner diameter ($d$/mm)</td>
<td>60</td>
</tr>
<tr>
<td>bearing's outer diameter ($D$/mm)</td>
<td>95</td>
</tr>
<tr>
<td>axial load $N$</td>
<td>150</td>
</tr>
<tr>
<td>Radial load $N$</td>
<td>180</td>
</tr>
<tr>
<td>$f_0$</td>
<td>6</td>
</tr>
<tr>
<td>$f_1$</td>
<td>$5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

**Table 1: Parameters of certain sealed spherical roller bearing**

The combined influence of the over surplus assembly, micro components on the material surface and the surface roughness in bearing structure makes the bearing friction coefficient drift mechanism complicated and difficult to figure out.

With the axial and radial loads as shown in Table 1, the creep model of roller bearing friction coefficient of certain inertial platform system drift along with temperature and time can be concluded as follow:

$$\mu = 0.0135 \ln(t) + 0.1273 \quad (6)$$

Combine equation (4), (5), (6) and the data in Table 1, the drift mechanism model of the bearing friction coefficient can be concluded as follow:

$$M = 10^{-7} f_0 (vn)^{2/3} D_0^2 + (\mu f_F D_0) / 2$$

$$= 10^{-7} \times 6(0.05 \times 10^{-12} + 0.0147 \times (0.835 \times \log t + 2.47) \times 30)^{2/3} \times 77.5$$

$$+ (0.0135 \ln t + 0.1273) \times 5 \times 10^{-4} \times \sqrt{[5(0.835 \times \log t + 2.47)] + 77.5} / 2 \quad (7)$$

$$= 0.3659743 \times [10^{-12} + 0.0147 \times (0.835 \times \log t + 2.47)]^{2/3}$$

$$+ 0.0613 \ln t + 0.5779$$

**Analysis of heading sensitive drift model parameter drift behavior**

Heading sensitive drift expression caused by servo loop zero and structure disturbing torque is related to the preamplifier scale factor $K_p$, sensor scale factors $K_{p1}, K_{p2}$, gyro angular momentum $H$, gyro time constant $\tau$, residual elastic coefficient $\Delta k$, drift angle of traverse gyro rotor $Y$ axis and $X$ axis $\beta$, and servo loop stiffness $S_v$, the paper studied there parameters respectively.

**Scale factor of preamplifier:** The degradation rule of the preamplifier is similar to that of the resistor and capacitor, and according to the acceleration characteristic of analog electronic products, we choose the Arrhenius as the preamplifier behavior model, which suitable for mainly affected by temperature situation [18].

Through the experiment analysis of preamplifier’s key resistor drift characteristic, we can get the preamplifier behavior model with the initial value $K_p = 50$ as follow:

$$K_p = 50(17.4132 - 1.04775 \times 10^{-4} \times t - 0.00139899 \times T + 2.31568 \times 10^{-5} \times t^2 + 2.35779 \times 10^{-6} \times T^2 + 2.9888 \times 10^{-7} \times t \times T) \quad (8)$$

**Scale factor of sensor:** Sensor, which takes many forms, is a measuring system composed of sensitive components and measuring circuit, and the sensor used in dynamically tuned gyro is variable reluctance inductive sensor [19].

The derivation expression of variable reluctance inductive sensor is as follow [13]:

$$K_p = \frac{U}{(2\Delta \delta)} \quad (9)$$

Where, $K_p$ is the scale factor of sensor, $\delta$ is the initial clearance between iron core and magnetic conductance ring, $\Delta R = r a, r$ is the center diameter of the sensor’s iron core, and $a$ is the rotating angle of gyro rotor.

Engineering experience has proved that the drift of sensor scale fac-
Drift angle of azimuth gyro around X axis: The X axis of azimuth gyro connected to inertial platform structure by the self-locking loop, and thus $\beta_2$ only depends on the loop zero and its output of the self-locking loop, which do not change with heading angle. The functional block diagram of gyro X axis' work on the servo loop is shown in Figure 5 [13].

Gyro sensor converts the rotate angle of the X axis into electrical signal and transmits it into the lock-in amplifier, which then supplies the gyro torque with current proportionate to the electrical signal, and finally the gyro torque produces moment to enable the rotation of gyro until the gyro H axis is brought to zero.

Therefore, the behavior characteristic of the drift angle of azimuth gyro around X axis is the same with the servo loop zero in terms of behavior. The drift behavior model of the drift angle of the azimuth gyro around X axis with an initial value $\beta_1 = 1.5 \times 10^{-4}$ rad = (270/π)\times10^{-6} can be concluded according to equation (3) below:

$$\beta_2 = \frac{(270/\pi)\times10^{-6} \times (-x)}{2.31568 \times 10^{-9} \times T + 2.35779 \times 10^{-5} \times T + 2.9888 \times 10^{-10}} (15)$$

Stiffness of servo loop: The principle of servo loop stiffness is as follows [20]:

$$S_s(s) = \frac{M_{s}(s)}{\Theta(s)} = K_s K_s F(s) / R (16)$$

Where, $K_s = H/C$, and C is the viscous damping coefficient, $K_s$ is the motor torque coefficient, $R$ is the total resistance of torque motor, $K_F(s)$ is the transfer function of servo amplifier, $K_s$ is the total magnification of servo amplifier, $F(s)$ is the network transfer function, and $J$ is the total moment inertia of the torque motor around output shaft.

From the above analysis, it can be seen that the acceleration of the servo loop stiffness depends on the performance of the servo loop, and thus has the same degradation characteristic with the servo loop. By referring to equation (3) above, the drift behavior model of servo loop stiffness with an initial value of $S_s = 5 \times 10^{-4}$ g•cm/rad = (50\pi/18) kg•m/s can be concluded as follows:

$$S_s = \frac{(50\pi/18) \times (7.4132 - 0.19775 \times T + 0.0018789 \times T^2 + 2.31568 \times 10^{-9} \times T + 2.35779 \times 10^{-5} \times T^2 + 2.9888 \times 10^{-10} \times T)}{2.31568 \times 10^{-9} \times T + 2.35779 \times 10^{-5} \times T^2 + 2.9888 \times 10^{-10} \times T} (17)$$

Drift behavioral model for the heading sensitive drift of inertial platform system

Inserting equations (3) – (17) into equation (1) and (2), i.e. heading sensitive drift caused by servo loop zero and structure disturbing torque respectively, we can easily get the synthetic drift behavioral model with $M_x = M_y = M_z$ and unified parameters unit. In order to analyze the model in a more vivid and effective way, this paper applies the response surface identification method to rewrite the mechanism equation (1) and (2), and results in equation (18) as below:

$$\omega_0 = \omega_x + \omega_y + \omega_z = 0.013528735853104 - 1.0606312285 \times 10^{-8} g - 5.3737145165 \times 10^{-7} T - 4.23727461 \times 10^{-2} T + 1.759374 \times 10^{-4} \times g T + 7.6392 \times 10^{-4} \times T + 2.45142 \times 10^{-5} T + 1.84714399 \times 10^{-10} T^2 + 5.138001 \times 10^{-10} T^2 + 1.2679 \times 10^{-12} \times T + 0.901256402152763 - 8.33169068108 \times 10^{-8} \times T - 4.06027696664 \times 10^{-7} T + 5.279128685 \times 10^{-11} T + 1.47853436 \times 10^{-7} g (18)$$
\[ x = x_0 + \omega_y \cdot \Delta t + \omega_{yy} \cdot \Delta t^2 \]
easily found that heading sensitive drift has similar drift characteristic on X, Y and Z axis under long-term storage conditions, and this phenomenon is different from that under the operating conditions, as under operating conditions, drift on X axis and Y axis is larger than that on Z axis [1].

Acceleration feature analysis: From Figure 8-10, it can be easily found that the temperature change has little influence on the heading sensitive drift, but the drift is obvious under long-term storage condition for the first time, which has provided theoretical support for the heading sensitive drift behavior analysis of inertial platform system with the feature of “long-term storage and one time using”.

(2) Through deep analysis of the mechanism of bearing friction torque and behavioral of heading sensitive drift model parameters, the paper has deduced the behavioral model of inertial platform system’s heading sensitive drift, and has vividly presented the long-term drift behavioral performance along with temperature and time by system identification method.

(3) Through the analysis of heading sensitive drift's storage behavior, the paper concludes that the heading sensitive drift caused by servo loop zero and structure disturbing torque does not have acceleration feature, and the stability drift value, while meeting the requirement of long-term stability, still contribute a lot to the whole system's drift. The conclusion and finding is of great significance for guiding the resources allocation for the calibration and maintenance in inertial platform system.

References


