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Research on Heading Sensitive Drift Behavior of Inertial Platform System under the Influence of Magnetic Field

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The heading sensitive drift of inertial platform system changes along with the degradation of components' performance and the coupling characteristics under long-term storage conditions. Such heading sensitive drift is different from the drift during operation. It is also difficult to analyze its drift behavior for the model-based PHM system designing of inertial platform systems in engineering application. While the heading sensitive drift is influenced by various factors, this paper aims at dealing with part of this problem from one of the factors, i.e. magnetic field influence. This paper at the beginning derived the principle and the expression of the heading sensitive drift caused by magnetic field. And then, various drift parameters in such expressions were discussed, and the behavioral model of the heading sensitive drift influenced by the magnetic feature of components (such as the sensor, the torquer and the gyrorotor) was obtained. Finally, the long-term drift feature, the acceleration feature and the storage stability of the heading sensitive drift behavior were analyzed with the actual storage profile. The results of this paper indicate that although the heading sensitive drift caused by magnetic field has acceleration feature, the stability is able to meet the accuracy requirement of the inertial platform system under the current storage conditions. The drift value is so small that it can be ignored under the storage conditions. This study has great significance to the model-based PHM system design of inertial platform systems, which aims at improving the inertial platform systems parameters stability.

1. Introduction

Heading sensitive drift mainly refers to the phenomenon of the gyro's drift along with the heading attitude's change in the inertial platform system. The drift value is over a dozen or dozens of times of the gyro precision level. Besides, the stability level of the heading sensitive drift is also hardly predictable. For such reasons, it has become a difficult issues in the research on precision of inertial platform system both at home and abroad (Hu Pinghua/2000, Fredric Nadeau/1995, Zhang Dong-rong&Ye Bin/2010).
Researches show that, based on its action principles, there are four factors that influence the heading sensitive drift, including 1) servo loop zero and structure disturbing torque, 2) vibration, 3) temperature and 4) magnetic field. During actual operation, measures such as Kalman filtering technique and GPS/INS integrated navigation technology are often employed to ensure the accuracy of the performance parameters of the inertial platform system (Hu Pinghua/2000, L.R.Sahawneh/2011, Arunasish&Acharya/2011). Since the heading sensitive drift is a major performance parameter of the system, to improve the accuracy of the heading sensitive drift will largely help to improve that of the whole system. However, for the missile inertial platform system which is subject to long-term storage and use for only once, the magnetic components inside the system, such as the sensor and the permanent magnet torque, will get degraded. Under long-term storage, the magnetism of such components is influenced by the geomagnetic field and the disturbance torque of external magnetic field. This will severely impacts the storage behavior of the heading sensitive drift of the inertial platform system. The influencing mechanism of those factors is complex and is quite different from the drift under operating conditions. This paper will first discuss the influence principle of the magnetic field on the heading sensitive drift and its expression. And then, the drifting characteristics of the parameters in the expression will be analyzed through both theoretical and experimental research. The behavioral model of the heading sensitive drift under the influence of magnetic field will be obtained. Ultimately, the long-time drift characteristic, acceleration performance and stability of heading sensitive drift are to be analyzed by employing an actual storage condition profile. The results indicate that although the heading sensitive drift caused by magnetic field has the acceleration effect, the stability can meet the accuracy requirement of the inertial platform system under the current storage conditions. The drift value is so small that it can be ignored under the storage

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conditions. The research is critical for reasonable resource allocation in respect of the calibration and maintenance in inertial platform system.

2. Principle of heading sensitive drift of the inertial platform system caused by the magnetic field

2.1 Research object

Figure 1 is the frame structure of the inertial platform system, i.e., the research object of this paper. The system is mainly composed of the azimuth ring, the pitch ring, the rolling ring and other connecting structures. It provides measured value of the pitch angle, the roll angle and the azimuth angle for the device's missile attitude control through attitude angle sensor on the gimbal axis of the platform (Chen Yongbing&Zhong Bin/2007).

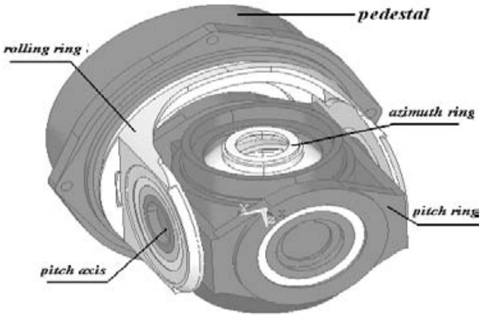

Figure 1 Frame structure of inertial platform system

Under the long-term storage influence of magnetic disturbance torque, the performance parameters of the magnetic sensor and those structures that are easily magnetized will get degraded. As a result, the gyro will output additional drift related to the long-term storage action of the magnetic disturbance, specifically, change in the storage behavior of the heading sensitive drift.

2.2 Principle of heading sensitive drift of the inertial platform system caused by the magnetic field

The influence of magnetic field on the heading sensitive drift mainly refers to the influence of external magnetic field on magnetic components such as the inductive sensor, the permanent magnetic torque, and the hysteresis synchronous motor, as well as soft magnetic materials like the gyrorotor, the base and the end cap. Engineering application shows that the drift is mainly influenced by uniform magnetic field. It can be deduced from the literature (Hu Pinghua/2000) that the total disturbance torque influenced by the uniform magnetic field can be expressed as follows:

$$\begin{aligned} M_{DX} &= K_{PE}\beta + K_{TE}\beta + K_{RE}\beta \\ M_{DY} &= K_{PE}\alpha + K_{TE}\alpha + K_{RE}\alpha \end{aligned} \tag{1}$$

where, M_{DX} and M_{DY} stand for the total disturbance torque on the X axis and Y axis of the gyro caused by the uniform magnetic field respectively, K_{PE} is the sensor's electromagnetic torque, K_{TE} is the disturbance torque coefficient at the zero position of the torquer, K_{RE} is the leakage magnetic torque coefficient surrounding the rotor, and α and β are the deviation angles of the gyrorotor.

In line with the principle by which the disturbance torque of the inertial platform system causes the heading sensitive drift (Hu Pinghua/2000), we can obtain the expression of the heading sensitive drift caused by the magnetic disturbance torque of the inertial platform system as follows:

$$\begin{aligned} \omega_{PX} &= \frac{1}{\tau S_0}\left(M_{DX}\cos\psi - M_{DY}\sin\psi\right) - \frac{\Delta k}{HS_0}\left(M_{DX}\sin\psi + M_{DY}\cos\psi\right) \\ \omega_{PY} &= \frac{1}{\tau S_0}\left(M_{DX}\sin\psi + M_{DY}\cos\psi\right) + \frac{\Delta k}{HS_0}\left(M_{DX}\cos\psi - M_{DY}\sin\psi\right) \end{aligned} \tag{2}$$

where, ω_{PX} and ω_{PY} are the additional drift output from the gyro's X axis and Y axis, that is, the heading sensitive drift; M_{DX} and M_{DY} are the magnetic field disturbance torque on the gyro's X axis and Y axis respectively, g·cm; τ is the time constant of the vertical gyro and the azimuth gyro, s; S_0 is the servo loop rigidity, g·cm/rad; H is the moment of inertial of the gyro, kg·m^2/s; and $\triangle k$ is the residual elasticity coefficient of the gyro, g·cm/rad.

3. Storage behavioral model of the heading sensitive drift of the inertial platform system caused by the magnetic field

In the passages below, this paper is going to make a thorough analysis of the storage features of the magnetic effect of the sensor's electromagnetic torque coefficient K_{PE}, the disturbance torque coefficient at the zero position of the torquer K_{TE}, and the leakage magnetic torque coefficient surrounding the rotor K_{RE}.

3.1 Storage behavioral model of parameters with magnetic characteristic

Under the long-term storage conditions, the uniform magnetic field mainly impacts the electromagnetic damping coefficient of the gyrorotor, which then lead to changes of relevant coefficients such as the sensor's electromagnetic torque coefficient, the disturbance coefficient at the torquer's zero position and the leakage magnetic torque coefficient surrounding the rotor. It is assumed in this paper that the magnetism degradation effect of all components is the same, and such characteristic can be reflected by the surface magnetic density of the gyro's soft magnetic materials. Therefore, based on theoretical analysis (Zhu Zhongping/2003), we can get the storage characteristics of the gyro shell 1J79 soft magnetic material of the inertial platform system through experimental measurements and Arrhenius model deduction:

$$\Delta B_r = 0.07 \times \exp\left(-\frac{2357-E}{8.314T}\right) \times \ln t \tag{3}$$

where $\triangle B_r$ is the surface magnetic density; E is the external magnetic field intensity, whose unit is G_s; the unit of T is K; and the unit of t is hour.

➢ **The Sensor's electromagnetic torque**

The initial design value of the sensor's electromagnetic torque of a certain platform system is K_{PE}=0.97734×10^{-5} N·m/rad. Multiply this value with Equation (3), i.e., the magnetism degradation effect coefficient, and we can get the storage behavioral model of the sensor's electromagnetic torque coefficient under the influence of uniform magnetic field as follows:

$$K_{PE} = 6.8414 \times 10^{-7} \times \exp\left(-\frac{2357-E}{8.314T}\right) \times \ln t \tag{4}$$

➢ **Disturbance torque coefficient at the zero position of the torquer**

The initial design value of the disturbance torque coefficient at the torquer's zero position of a certain platform system is K_{RE}=3.2171kg·m/A. Multiply the above value with Equation (3), i.e., the magnetism degradation effect coefficient, and we can get the storage behavioral model of the sensor's electromagnetic torque coefficient under the influence of uniform magnetic field as follows:

$$K_{RE} = 0.225197 \times \exp\left(-\frac{2357-E}{8.314T}\right) \times \ln t \tag{5}$$

➢ **Leakage magnetic torque coefficient surrounding the rotor**

The initial design value of the leakage magnetic torque coefficient surrounding the rotor of a certain inertial platform system is K_{RE}=1.568167N·m·h/r. Multiply the above value with Equation (3), i.e., the magnetism degradation effect coefficient, and we can get the storage behavioral model of the sensor's electromagnetic torque coefficient under the influence of uniform magnetic field as follows:

$$K_{RE} = 0.109772 \times \exp\left(-\frac{2357-E}{8.314T}\right) \times \ln t \tag{6}$$

3.2 Storage behavioral models of other parameters

It can be seen from Equation (2) that, apart from the electromagnetic torque coefficient, the disturbance torque coefficient at the torquer's zero position and the leakage magnetic torque coefficient surrounding the rotor, there are also other causes of the heading sensitive drift of the inertial platform system. Such causes include but are not limited to the rotor's deviation angles α and β, the gyro's time constant τ, the servo loop rigidity S_0, the residual elasticity coefficient $\triangle k$ and the gyro's angular momentum H. These parameters are mainly influenced by the temperature stress which inevitably exists under storage condition, and will show certain drifting characteristics under the long-term temperature stress. Here below is a detailed study of all these parameters in the storage behavioral model.

➢ **Rotor's deviation angle (sensor's zero position)**

The output information of the gyro's X axis and Y axis acts on the inertial platform system through the feedback of the servo loop. Hence, we can take the temperature characteristic of the servo loop as that of the rotor's initial drift angle. By analyzing the temperature characteristic of the servo loop's temperature characteristic, we can get the storage behavioral model of the rotor's initial deviation angle (the sensor's zero's position) as follows (Pan Ronglin/1990, Hu Pinghua/2000):

$$\begin{aligned}
\alpha &= (61.2/\pi)\times 10^{-3} \times (17.4132 - 1.04775\times 10^{-4} \times \mathrm{t} - 0.00139899\times T \\
&+ 2.31568\times 10^{-9} \times t^2 + 2.35779\times 10^{-8}\times T^2 + 2.9888\times 10^{-9}\times t\times T) \\
\beta &= (270/\pi)\times 10^{-3} \times (17.4132 - 1.04775\times 10^{-4} \times \mathrm{t} - 0.00139899\times T \\
&+ 2.31568\times 10^{-9} \times t^2 + 2.35779\times 10^{-8}\times T^2 + 2.9888\times 10^{-9}\times t\times T)
\end{aligned} \tag{7}$$

➢ **Gyro's time constant**

The calculation of the gyro's time constant is as follows (Pan Ronglin/1990):

$$\tau = H/\lambda = J_z/(\xi+\delta) \tag{8}$$

where, J_Z is the moment of inertia of rotor's polar axis, ξ is the rotor's gas damping coefficient, δ is the internal friction damping coefficient of the flexible joint, and λ is the orthogonal damping elasticity coefficient.

It can be known from the above parameters that the gyro’s constant is mainly influenced by the damping feature of the materials. Therefore, the temperature feature of the damping coefficient of the materials can be used to reflect the temperature feature of the gyro’s time constant. By introducing the concept of equivalent viscous damping, this paper converts the gyro's damping into equivalent viscous damping (the conversion method is to deem that viscous damping consumes the same energy with other viscous damping in a vibration cycle), and take it as the temperature coefficient of the gyro time constant. Ultimately, the behavioral model of the gyro's time constant in a certain inertial platform system with an initial value of $\tau = 60s$ is as follows:

$$\tau_1 = 54.2821 \times (0.421652122 \times 10^{-8} \times e^{19.35 - 18.51/T}) \times \ln t \tag{9}$$

➢ **Servo loop rigidity**

The expression of the servo loop rigidity is (Pan Ronglin/1990):

$$S_0(s) = \frac{1}{\varphi(s)} = \frac{M_D(s)}{\theta(s)} = Js^2 + K_g K_a^{'} K_m F(s)/R \tag{10}$$

where, K_g=H/C and C is the viscous damping coefficient, K_m is the torque coefficient of the electric motor, R is the total resistance of the torque motor, $K^{'}_{a} F(s)$ is the transfer function of the servo amplifier, $K_a^{'}$ is the total magnification of the servo amplifier, *F(s)* is the network transfer function and *J* is Total moment of inertial of the torque motor rotating around the output shaft.

It can be seen that the change of the servo loop rigidity depends on the temperature effect of the servo loop. Hence, the storage behavioral model of the servo loop rigidity can be obtained from Equation (7):

$$\begin{aligned} S_0 = &(50\pi/18) \times (17.4132 - 1.04775 \times 10^{-4} \times \mathrm{t} - 0.00139899 \times T \\ &+ 2.31568 \times 10^{-9} \times t^2 + 2.35779 \times 10^{-8} \times T^2 + 2.9888 \times 10^{-9} \times t \times T) \end{aligned} \tag{11}$$

➢ **Residual elasticity coefficient**

The residual elasticity coefficient is defined as follows (Pan Ronglin/1990):

$$\Delta k = K_0 - (a + b - c) N^2 / 2 \tag{12}$$

Generally, once the parameters of the flexible supporting structure have been determined, the adjustable parameters mainly include the moment of inertia *a*, *b* and *c*, and the rotating speed *N*. Therefore, the storage characteristic of the residual elasticity is mainly related to the rigidity of the gyro's material. Through experiment of the temperature characteristic of the gyro material rigidity, and taking it as that of the residual elasticity coefficient, we can get the storage behavioral model of the residual elasticity as follows:

$$\Delta k = \frac{\pi}{360} \times 10^{-5} \times \frac{3 \times 10^8 - \dfrac{1}{\sqrt{2.3275 \times 10^{-16} t \exp(-26.6/8.31T)}}}{1.75 \times 10^{11}} \tag{13}$$

➢ **Gyro’s angular momentum**

The expression of the gyro’s angular momentum is (Pan Ronglin/1990):

$$H = J_z \omega \tag{14}$$

It can be known from the above expression that the gyro’s angular momentum mainly depends on the design parameters and will not change with time or temperature. Therefore, the initial design value is set at $H = 74.088 kg \bullet m^2 / s$.

3.3 Storage behavioral model of heading sensitive drift of inertial platform system caused by the magnetic field

Insert equations from Equation (3) to Equation (14) into Equation (2) and unify the units of all parameters, and we can obtain the storage behavioral model of the heading sensitive drift of the inertial platform system under the influence of the magnetic field. In order to analyze the model effectively, this paper uses the response surface identification method [9] to get a brief storage behavioral identification model as shown in Equation (15) below:

$$\begin{cases} \omega_{PX} = 0.341219315687886 \times 10^{-4} + 0.1263633001923 \times 10^{-6} \times E + 0.8376157718625 \times 10^{-6} T + 0.742 \times 10^{-16} t \\ \quad -0.1330962847 \times 10^{-9} \times E \times T - 0.2 \times 10^{-18} \times T \times t + 0.155333485 \times 10^{-10} \times E^2 + 0.7768987387 \times 10^{-9} \times T^2 \\ \omega_{PY} = 0.773430681067779 \times 10^{-5} + 0.2864225241321 \times 10^{-7} \times E + 0.18985955985011 \times 10^{-6} T + 0.3351 \times 10^{-16} t \\ -3016842984 \times 10^{-10} \times E \times T - 0.4 \times 10^{-19} \times T \times t + 0.353465779 \times 10^{-11} \times E^2 + 0.17609702236 \times 10^{-9} \times T^2 \end{cases} \tag{15}$$

4. Analysis of the storage behavior of the heading sensitive drift of inertial platform system caused by the magnetic field

Simulating Equation (15) by Matlab with the heading angle set at zero, we can get the data of inertial platform system's heading sensitive drift within a period of ten years under normal storage temperatures with different magnetic field intensities (the range of the magnetic field intensity during the assembling and the debugging of the inertial platform system is 0.2Gs~1.0Gs) .The results are shown in Table 1 as follows.

Table 1 Data for the storage behavior of inertial platform system's heading sensitive caused by magnetic field

Drift time (year)		1	2	3	4	5	6	7	8	9	10
heading sensitive drift on X axis (10^{-4}°/h)	0.2 Gs	2.1294936405	2.1294936404	2.1294936404	2.1294936404	2.1294936403	2.129493640	2.129493640	2.1294936403	2.1294936403	2.1294936403
	0.4 Gs	2.1296683934	2.1296683933	2.1296683932	2.1296683932	2.1296683932	2.1296683932	2.1296683931	2.1296683931	2.1296683931	2.1296683931
	0.6 Gs	2.1298431606	2.1298431605	2.1298431604	2.1298431604	2.1298431604	2.1298431603	2.1298431603	2.1298431603	2.1298431603	2.1298431603
	0.8 Gs	2.1300179421	2.1300179420	2.1300179419	2.1300179419	2.1300179419	2.1300179419	2.1300179418	2.1300179418	2.1300179418	2.1300179418
	1Gs	2.1301927380	2.1301927379	2.1301927378	2.1301927378	2.1301927377	2.1301927377	2.1301927377	2.1301927377	2.1301927377	2.1301927377
heading sensitive drift on Y axis(10^{-5}°/h)	0.2 Gs	4.826852262	4.826852266	4.826852269	4.826852270	4.826852271	4.826852272	4.826852273	4.826852273	4.826852274	4.826852274
	0.4 Gs	4.827248368	4.827248373	4.827248375	4.827248377	4.827248378	4.827248379	4.827248379	4.827248380	4.827248380	4.827248381
	0.6 Gs	4.8276445074	4.827644512	4.827644514	4.827644516	4.827644517	4.827644518	4.827644518	4.827644519	4.827644519	4.827644520
	0.8 Gs	4.828040679	4.828040683	4.828040686	4.828040687	4.828040688	4.828040689	4.828040690	4.828040690	4.828040691	4.828040691
	1Gs	4.828436883	4.828436887	4.8284368895	4.828436891	4.828436892	4.828436893	4.828436894	4.828436894	4.828436895	4.828436895

Fit the data in Table 1, and we can get the drift curve indicating the drift value variation with magnetic field and almost constant with storage time.

➢ Long-term drifting characteristic

It can be seen from Table 1, the heading sensitive drift level stays at about 10^{-4}°/h and can meet the accuracy requirement (0.01°/h) of the inertial platform system under the current storage conditions. The drift value is so small that it can be ignored under the storage conditions

➢ Acceleration effect

It can be found from Table 1 that there are leaps among the heading sensitive drift of the inertial platform system under different magnetic fields, but the drift law remains unchanged. Therefore, it means that the magnetic field has the acceleration effect for the heading sensitive drift.

➢ Storage stability

The magnetic field intensity of a storeroom without electric power of a certain inertial platform system is 0.3Gs. The average storage temperature is 20℃; the heading sensitive drift will be calibrated within a cycle of every 12 months; the magnetic field intensity during the calibration with electric power is 0.4Gs; the calibration temperature is 70℃ duration of calibration is 48 hours. The paper simulates the accumulative drift value upon expiration of every cycle and analyzes its storage stability with the results shown in Table 2.

Table 2 Stability analysis results of the heading sensitive drift of the inertial platform system

Storage cycle (year)	heading sensitive drift stability on X axis(10^{-13}°/h)	heading sensitive drift stability on Y axis(10^{-13}°/h)
1	2.0739899	9.1499370
2	2.1730897	9.5871861
3	2.2243996	9.8135410
4	2.2582194	9.9627680
5	2.2831295	10.0726470
6	2.3026893	10.1589030
7	2.3186891	10.2295161
8	2.3321891	10.2890610
9	2.3438190	10.3403910
10	2.3423890	10.3340700

Fit the accumulative heading sensitive drift on X axis and Y axis in Table 2, and we can get the curve in Figure 2 as follows:

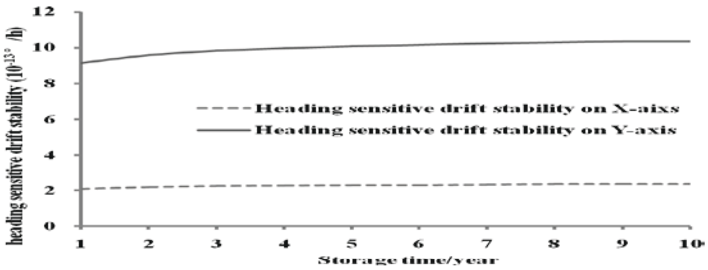

Figure 2 Curve for the accumulative heading sensitive drift in inertial platform system

It can be found from Table 2 and Figure 2 that the heading sensitive drift on the gyro's X axis and Y axis diverges greatly, but the drift value stays stable at about 10^{-13}. Such drift value can be ignored since the stability requirement for one year in current engineering is set at 0.2℃/h (which means the maximum drift difference≤0.2℃/h). Therefore, the influence of the magnetic field can be disregarded in the resources allocation for the calibration and maintenance in inertial platform system.

5. Conclusion

This paper has derived the heading sensitive drift behavioral model of the inertial platform system under the influence of uniform magnetic field. Through comprehensive analysis of the storage characteristics in the behavioral model, this paper has pointed out that the influence of magnetic field on the heading sensitive drift of the inertial platform system can be ignored. The research approach and conclusion are meaningful not only to theoretical research but also engineering application.

The major contribution and innovative points are as follows:

1) This paper analyzed the heading sensitive drift mechanism caused by the magnetic field under the storage conditions .Its storage behavioral model has laid down a theoretic basis for future research on heading sensitive drift in the missile inertial platform system featuring long-term storage and one-time use.

2) The Matlab simulation indicates that the heading sensitive drift caused by magnetic field has an acceleration effect, but the drift value is so small that it can be ignored for navigation accuracy.

The conclusions and findings hereof are of great significance for resources allocation of the calibration and maintenance in inertial platform system, and support the model-based PHM design of the inertial platform systems in theory.

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