Control Signal Analysis of Four Ring Space Stabilized Platform

Minghao Gao, Yunhui Ning*, Yujie Wang, Gaoling Song and Zhipeng Zheng

Tianjin Institute of navigation instruments No.1, Dingzigu Road, Hongqiao District, Tianjin, China. Naval Research Institute, Beijing, China

*Corresponding author email: 847105038@qq.com

Abstract. In order to build a four ring space stable platform using free rotor gyroscope, the spatial layout of gyroscope and frame axis should be briefly analyzed, and the installation shafting should be orthogonal or perpendicular to each other to facilitate control and decoupling. On this basis, through the sensitive angle analysis of gyro and frame shafting, the control signals acting on each frame are deduced. Finally, through the physical design of the control loop of the space stability platform, the correctness of the research method and design form is demonstrated, which has theoretical guiding significance for the design of the space stability control loop.

1. Introduction

Space stabilized platform is a platform that keeps the platform attitude unchanged in inertial space by adjusting the platform traction axis according to the sensitive angle of fixed axis gyro. In the design and composition of high-precision inertial navigation system, a stable inertial coordinate system can be constructed through the spatial stable platform, and then the velocity and position information in the inertial system can be solved through the accelerometer data integration under the inertial system. Compared with the local horizontal stabilized platform, the space stabilized platform does not need to apply correction torque to the gyro in the process of inertial navigation, and has higher precision. Therefore, the space stabilized platform has become the research focus in the field of high-precision inertial navigation.

2. Structural Design of Four Ring Space Stable Platform

Theoretical analysis shows that in order to build a space stable platform, at least three orthogonal angle change information and three ring rotation frame are needed to adjust the platform attitude. Each free rotor gyroscope has two sensitive angles orthogonal to the momentum axis, so the platform needs two free rotor gyroscopes. Under some specific frame angle conditions, the insufficient torque application capacity of the motor leads to frame self-locking. A loop should be added and the control strategy should be adjusted to maintain the space stability of the platform. To sum up, the structure of the space stabilization platform shall include two free rotor gyroscopes, four ring frames and electromechanical components required for the torsion of each frame, including servo motor, angle sensing element, precision bearing and slip ring. In order to facilitate the decoupling of control signals, the mounting axes of the frame and the gyro shall be perpendicular or orthogonal to each other. The specific composition is shown in figure 1. For the convenience of later analysis, the frame angle position in the figure 1 is the frame zero position value.
It can be seen from Figure 1 that the outer, middle, inner and platform frames are involved with each other, and each frame has a degree of freedom in one direction. When the frames are located at the zero position in Figure 1, the outer frame axis and platform axis are parallel to the earth axis, the middle frame axis is parallel to the geographical East, the platform axis is parallel to the geographical North, and the momentum moment $H_p$ of the gyroscope fixed with the platform body points to the polar axis direction, which is called the polar axis gyroscope. The two sensitive angle axes are parallel to the middle frame and inner frame shafting respectively. The momentum moment $H_e$ of the other gyro points east and falls in the equatorial plane. It is called equatorial gyro. Its installation mode is usually divided into two types. One is to directly connect it to the platform and only use the sensitive angle signal parallel to the axis of the platform, and the other is to establish a redundant axis parallel to the redundant signal to connect the equatorial gyro to the redundant axis. In this way, the two sensitive angles are parallel to the platform axis and the redundant axis respectively. This paper will study the second method. When a single frame rotates and the other frame angles are at the zero position, the angle sensed by any gyro can be offset by the axis angle control adjustment of the axis parallel to it. This kind of height decoupling control method of adjusting the single axis according to the single gyro signal is easy to understand, and it is also the theoretical basis of spatial stability control under complex conditions.

Since the geographic coordinate system and inertial system do not coincide at each position on the earth's surface, when starting the gyro at any position, adjust the angle of the middle frame, rotate the local latitude angle, adjust the angle of the outer frame, rotate the heading angle of the base, and keep the zero value of the other frames, so that the polar axis, equatorial gyro and rotation moment axis can be adjusted to point to the correct position. After the gyro is started and enters the space stability mode, each frame should control the position of the frame according to the gyro sensitive angle information. Since the shafting involved in the gyro shell increases from the inside to the outside of the system, and the decoupling control signals of each frame become more and more complex, this paper will give priority to the analysis of equatorial gyro and redundant and station control signals.

3. Structural Design of Four Ring Space Stable Platform

3.1. Analysis of Equatorial Gyro Control Signal

As shown in figure 2, since the equatorial gyro and the redundant axis are fixedly connected with each other, the equatorial gyro $Ex$ sensitive axis and the redundant axis are always parallel to each other regardless of the position of each frame. Therefore, the redundant axis control signal $Er$ selects $Ex$. This means that when the equatorial gyro sensitive axis reaches the angle $Ex$, it only needs to drive the redundant axis to rotate through the gyro sensitive angle to ensure the spatial stability of the attitude.
angle of this axis. The control of the platform axis is slightly different. When the redundant axis turns an angle $\theta_R$ relative to the zero position value and no matter other frames are in any state, the signal sensed by the equatorial gyro $E_y$ is the cosine component of the axial attitude change of the platform, and the axial sensitive angle of the platform shall be $E_y/\cos(\theta_R)$. Therefore, the platform axis control signal is selected as $E_y/\cos(\theta_R)$ To ensure the spatial stability of the axial attitude angle of the platform.

![Figure 2](image1.png)

**Figure 2.** Decomposition schematic diagram of equatorial gyro control signal

### 3.2. Analysis of Polar Gyro Control Signal

As shown in figure 3, since the polar axis gyro is fixedly connected to the platform, there is a suspension angle $\theta_T$ with the relative zero position of the platform axis. The angle change sensed by the inner frame axis shall be the sum of the projection of the polar gyro sensitive angle $P_x$ and $P_y$ on the inner frame axis.

![Figure 3](image2.png)

**Figure 3.** Decomposition schematic diagram of inner frame control signal

As shown in figure 3, it can be obtained that the control signal $E_i$ of the inner frame axis is as follows:

$$E_i = P_x \cos(\theta_T) - P_y \sin(\theta_T)$$

Similarly, when the inner frame is in the zero position, the control signal $E_{m'}$ along the axis of the middle frame can be obtained as follows:

$$E_{m'} = P_x \sin(\theta_T) + P_y \cos(\theta_T)$$
In this special case, \( E_m' \) is perpendicular to the zero section plane of the inner frame and parallel to the axis of the middle frame. When the inner frame shaft rotates an angle \( \theta_I \) around the zero position as shown in figure 4, the sensitive signal is a cosine component of the middle frame shafting.

![Figure 4. Decomposition schematic diagram of middle frame control signal](image)

Therefore, the middle frame control signal is selected as follows:

\[
E_m = \frac{E_m' \cos(\theta_I)}{\cos(\theta_I)} = \frac{(P_x \sin(\theta_T) + P_y \cos(\theta_T))}{\cos(\theta_I)}
\]

To sum up, the control signals of redundant, middle, inner and console are selected as follows:

\[
E_r = E_x
\]

\[
E_t = E_y / \cos(\theta_R)
\]

\[
E_i = P_x \cos(\theta_T) - P_y \sin(\theta_T)
\]

\[
E_m = \frac{E_m' \cos(\theta_I)}{\cos(\theta_I)} = \frac{(P_x \sin(\theta_T) + P_y \cos(\theta_T))}{\cos(\theta_I)}
\]

3.3. Analysis of Outer Frame Control Signal at Low Latitude

Theoretically, if only the three ring combined with equatorial redundant axis structure is used for spatial stability control, the change of carrier attitude can be offset through the coordinated movement of the middle, inner and platform frame to realize the spatial stability control of the platform. Since the redundant axis and equatorial gyro are fixed on the platform, they also maintain spatial stability, so the redundant axis control signal and equatorial gyro sensitive signal \( E_x \) are constant at 0, That is, the redundant axis does not deflect and is always at the zero position of the redundant frame, as \( \theta_R \equiv 0 \). This also means that the middle frame control signal contains \( \cos(\theta_R) \) Divisor, but never goes to infinity. However, due to the continuous change of sensitive attitude, the relative deflection angle of the inner frame \( \theta_I \) may approaches 90°, the moment adjustment of the middle frame will approach infinity, which is obviously impossible for the motor in engineering reality. Therefore, the outer ring is usually added to maintain the spatial stability platform \( \theta_I \) is always zero, that is, the middle, inner and table shafts are always orthogonal in space, so as to keep the motor with sufficient driving torque.

The control signal of the outer frame is still analyzed from the simple case that the middle frame is at the zero position of the frame, as shown in figure 5, when the rotation angle of the inner frame shaft is \( \theta_I \), since the middle frame is at the zero position, the outer frame is parallel to the axis of the inner frame, so the outer frame needs to rotate at the same angle \( \theta_I \). Further, the effect of maintaining the internal state of the table shaft is the same as that of rotating the inner frame.
Therefore, when the middle frame is in the zero position, the outer frame control signal $E_0'$ is selected as follows:

$$E_0' = \theta_I$$

When the middle frame rotates $\theta_M$ degrees relative to the zero position is shown in figure 6.

When the inner frame is sensitive to an angle $\theta_I$, the relative rotation angle of the inner frame shall be kept to zero through the rotation of the outer frame, and the table body shall have the same state as the rotating inner frame. It can be seen from the figure that the outer frame shall rotate at this time, that is, the outer frame control signal shall be selected as follows:

$$E_0 = \theta_I / \cos(\theta_M)$$

3.4. Analysis of Outer Frame Control Signal at High Latitude

In the design of the above four ring space stable platform, the relative zero deflection angle of the middle frame $\theta_M$ will reflect the change of carrier latitude and attitude in latitude direction in navigation. When the system runs near high latitude, $\theta_M$ is large and the outer frame motor is required to provide large torque. Therefore, in high latitudes, the outer frame control mode is usually
switched to the mode of keeping the relative rotation angle of the platform constant, as shown in figure 7.

![Figure 7. Frame control signal diagram at high latitude](image)

At this time, in order to maintain the spatial stability of the platform, the rotation angle of the outer frame and the rotation angle sensitive to the platform need to be projected twice. The following formula is obtained.

\[ Eo' = \theta_T / \cos(\theta_i) \]
\[ Eo = Eo'/\sin(\theta_M) = \theta_T / (\sin(\theta_M)\cos(\theta_i)) \]

4. Design of Space Stability Control System

Through the geometric analysis of platform angle and gyro position, the control signal selection of each frame has been completed above. Through the analysis of the mathematical model of the control signal and the control object motor, the control loop of the four ring space stability platform is constructed, as shown in figure 8. The parameters of the illustrated loop are designed through the design methods of spectrum analysis, amplitude frequency analysis and parameter setting, and finally the high-precision stability control of the four ring space stability platform is realized.

![Figure 8. Schematic diagram of private server system of space stability platform](image)

5. Static Test Analysis of Space Stabilized Platform

Under static conditions, the input data (difference between the expected position and the actual position frame) of the position loop correction network of the spatial stability platform can be obtained,
and the control error curve and frame angular motion curve of each frame can be obtained, as shown in figure 9 and figure 10.

**Figure 9.** Control error analysis diagram

**Figure 10.** Frame motion analysis diagram

It can be seen from the figure that under static conditions, the axis system of each frame of the space stable platform has the same rotation law as the earth, that is, the axis of the platform maintains a uniform rotation of 15 ° / s, and the other frames remain constant. Therefore, the tracking relationship of the space stable platform to the inertial system can be proved. In addition, under the action of the control loop of the four ring space stabilization platform, the tracking error of each frame to the gyro is kept within 5 angular seconds, which demonstrates the engineering application value of the control loop in this paper.

6. Conclusion
Firstly, this paper briefly introduces the four ring space stabilization platform from the spatial position and the deployment mechanism of gyro loop, and then gradually separates the control signals that the space stabilization platform should act on each frame by graphical method. Through the design of
servo control loop, this paper demonstrates the correctness of control signal decomposition and the control ability of the whole loop. Through the analysis of this paper, the conclusions are as follows:

- In this paper, the grating angle measurement method is studied, including the analysis of grating angle measurement principle, the uniform design of double reading heads, the construction of grating angle measurement test platform, and the design of grating angle rotation servo control system. The physical platform is built and a set of standard angle error measurement method design is provided.
- In this paper, the repeatability test of three groups of grating angle measurement experiments is completed. The test proves that the angle measurement error under the same angle reference is less than 1.4 angular seconds, which shows that the grating angle measurement error law is obvious and the angle measurement error repeatability is good.
- Aiming at the angle measurement error of grating, the multi-method compensation method is studied in this paper. Finally, the harmonic compensation model is selected as the error compensation model. Aiming at the problem of zero crossing oscillation of the compensation algorithm, the piecewise compensation strategy is designed. The data simulation shows that the angle measurement error after compensation is less than 1.5 angular seconds, which has high engineering application value in the field of high-precision angle measurement.

7. References
[1] Chen Wen. Research on Key Technologies of attitude measurement of space stabilized platform inertial navigation system [D]. Precision instruments and machinery of Tsinghua University, April 2016
[2] Shtessel Y B. Decentralized sliding mode control in inertial navigation systems [C] Proc American Control Conf. Seattle, Washington, USA: AACC, 1995: 3541-3545
[3] Barnes F N. Stable-member mounted instrument environment simulation model development [J]. IEEE Transactions on Aerospace and Electronic Systems, 1972, 8(6):780-790
[4] Ellis G, Gao Zhi-qiang , Cures for low-frequency mechanical resonance in industrial servo systems[C] Industry Applications Conference ,Thirty-Sixth IAS Annual Meeting , Conference Record of the 2001 IEEE,2001:252-258
[5] Li Haixia, Gao Zhongyu. Kinematic analysis and motor torque calculation of four ring space stable platform [J]. Journal of Tsinghua University, 2007, 47 (5)
[6] Liu Yanbin, Jin Guang, He HuiYang. Model of three axis simulator and decoupling control [J]. Journal of Harbin Institute of Technology, 2003, 15 (3)
[7] Zhao Xia, Yao Yu, Fang Qiang. Application of step identification method in turntable servo system debugging [J]. Control theory and Application, 2002, 19 (2)