Analysis of the Influence of Mass Imbalance on the Performance of Photoelectric Stabilization Platform

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Abstract. Photoelectric stabilization platform is an optoelectronic imaging tracking system widely used in aircraft, vehicles and other equipment. It can effectively isolate the disturbance of the carrier and ensure the stability of the platform. In practical applications, there are many factors that affect the stability of the platform, including friction, disturbance, and mass imbalance. The purpose of this paper is to use Simulink to model and simulate the integrated three-axis photoelectric stability platform, and to explore the influence of mass imbalance torque caused by different factors on the accuracy and stability of the photoelectric stability platform. The results show that the unbalanced moment generated by the eccentricity of the frame has a great influence on the accuracy of the platform, and the unbalanced torque generated by the uneven mass distribution has little or no negligible influence on the accuracy of the platform.

1. Introduction
The photoelectric stability platform is an optoelectronic imaging tracking system consisting of three parts: photoelectric sensor system, signal processing and control system and tracking stabilization system [1]. It is generally a multi-axis, multi-frame spherical or hemispherical structure that can carry high-precision photoelectric loads such as visible light, infrared, and laser [2]. Since the photoelectric stabilization platform can not only effectively isolate the disturbance of the carrier, but also achieve fast and accurate capture, tracking and aiming of the moving target. Therefore, it has been widely used in modern weapons and equipment such as airplanes and ships.

In the analysis and design of the photoelectric stability platform system, it is very important to ensure its stability. There are many factors affecting the stability of the photoelectric stability platform, including friction, frame coupling, carrier disturbance and unbalanced disturbance. Yu Shuang et al. used sensors to test the frame, and derived the frame unbalanced moment formula in dynamic environment and established the inertial platform control model based on unbalanced torque compensation [3]. Wu Hailong et al. established a simulation model of mass static and dynamic imbalance for the two-frame stable platform, and studied its influence on the platform system [4]. Zhu Huazheng et al. used the two-frame seeker servo mechanism as the object to analyze the influence of mass static imbalance on the performance of the platform stability loop [5].

Although the above-mentioned references are all aimed at the modeling and simulation of the factors affecting the stability of the photoelectric platform, most of them ignore the modeling and simulation analysis of the unbalanced torque caused by the uneven distribution of the frame mass. Combined with the actual situation, this paper will model the simulation of the integrated three-axis three-frame photoelectric stability platform under the condition that the frame mass eccentricity and uneven mass distribution cause unbalanced torque, and study the influence of mass imbalance on the stability of the platform.
2. Kinematics Analysis

2.1. Coordinate System Definition
The three-axis stabilization platform consists of three frames, the structure of which is shown in Fig.1.

![Figure 1. Schematic diagram of three-axis stable platform structure and coordinate system.](image)

In Figure 1, \( o_b x_b y_b z_b \) is the pedestal coordinate system, and the origin is at the intersection of the three frame axes of the stable platform. \( o_m x_m y_m z_m \) is the outer frame (rolling frame) coordinate system, the roll axis \( o_x \) is in the same direction as \( o_b x_b \), and the rotation produces a roll angle of \( \alpha \). \( o_m x_m y_m z_m \) is the middle frame (azimuth frame) coordinate system, the azimuth axis \( o_x \) is in the same direction as \( o_m y_m \), and the rotation produces an azimuth angle of \( \beta \). \( o_m x_m y_m z_m \) is the inner frame (pitch frame) coordinate system, the pitch axis \( o_x \) is in the same direction as \( o_m y_m \), and the rotation produces the pitch angle \( \gamma \).

2.2. Analysis of Frame Motion Coupling Relationship
The coordinate transformation matrices from the base to the outer frame, the outer frame to the middle frame, and the middle frame to the inner frame are \( R_{ob} \), \( R_{mo} \), respectively. Let \( \omega_b = [\omega_{bx} \ \omega_{by} \ \omega_{bz}]^T \) be the angular velocity of the pedestal coordinate system with respect to the inertial space coordinate system. \( \dot{\alpha}, \dot{\beta}, \dot{\gamma} \) are the angular velocities of the outer frame, the middle frame, and the inner frame around the axis of rotation. According to the coupling relationship between the three frames of the platform, the angular velocity of the outer frame, middle frame, inner frame and detector's boresight in the inertial space coordinate system can be obtained as follows:

\[
\begin{align*}
\dot{\alpha} &= R_{ob} \omega_b + \begin{bmatrix} 0 & 0 \end{bmatrix}^T \\
\dot{\beta} &= R_{mo} \omega_b + \begin{bmatrix} 0 & 0 \end{bmatrix}^T + \dot{\beta} \\
\dot{\gamma} &= R_{mo} \omega_b + \begin{bmatrix} 0 & 0 \end{bmatrix}^T + \dot{\beta} + \dot{\gamma} \\
\dot{\epsilon} &= \omega_{i} \\
\end{align*}
\]

3. Quality Imbalence Model Analysis
Due to manufacturing and assembly errors, the quality imbalance of stable platforms is widespread. Generally, it consists of two parts: one part is due to the mass eccentricity of the frame, so that the frame produces an unbalanced torque in the presence of the carrier overload acceleration; the other part is due...
to the uneven distribution of the frame mass, that is, the product of inertia exists in the inertia tensor matrix. This produces an unbalanced torque.

3.1. Unbalanced Torque Generated by the Mass Eccentricity of the Frame

Define the overload acceleration at the origin of the stable platform base coordinate system as \( a_b = [a_{bx} \ a_{by} \ a_{bz}]^T \). According to the coordinate transformation relationship between frames, the acceleration of the outer frame, middle frame and inner frame are:

\[
a_o = R_{ob} a_b
\]
\[
a_m = R_{mo} a_o = R_{mo} R_{ob} a_b
\]
\[
a_i = R_{im} a_m = R_{im} R_{mo} R_{ob} a_b
\]

The projections of the outer frame, the middle frame and the inner frame centroid in the respective frame coordinate systems are \([r_{ox} \ r_{oy} \ r_{oz}], [r_{mx} \ r_{my} \ r_{mz}], [r_{ix} \ r_{iy} \ r_{iz}]\). The torque due to the force generated by the overload acceleration at the eccentricity can be expressed as:

\[
M = m \cdot a \cdot r
\]

Where \( m \) is the frame quality; \( a \) is the overload acceleration; \( r \) is the eccentricity.

Therefore, the mass imbalance torques on the outer frame axis, the middle frame axis and the inner frame axis are:

\[
M_{diso} = m \cdot (a_{ox} \cdot r_{oy} \cdot a_{oy} \cdot r_{ox})
\]
\[
M_{dism} = m \cdot (a_{my} \cdot r_{mx} \cdot a_{mx} \cdot r_{my})
\]
\[
M_{disi} = m \cdot (a_{ix} \cdot r_{iz} \cdot a_{iz} \cdot r_{ix})
\]

3.2. Unbalanced Moment Generated by Uneven Distribution of Frame Mass

Define \( J_i, J_m, \) and \( J_o \) as the inertia matrix of the inner frame, the middle frame, and the outer frame, respectively. \( \omega_i, \omega_m, \omega_o \) are the angular velocities of the inner frame, the middle frame, and the outer frame relative to the inertial space, respectively.

According to the momentum moment theorem, the dynamic model of the inner frame, the middle frame and the outer frame are:

\[
M_i = J_i \cdot \dot{\omega}_i + \omega_i \times J_i \cdot \dot{\omega}_i
\]
\[
M_m = J_m \cdot \dot{\omega}_m + \omega_m \times J_m \cdot \dot{\omega}_m + [M_i]_m = J_m \cdot \dot{\omega}_m + \omega_m \times J_m \cdot \omega_m + R_{mi} M_i
\]
\[
M_o = J_o \cdot \dot{\omega}_o + \omega_o \times J_o \cdot \dot{\omega}_o + [M_m]_o = J_o \cdot \dot{\omega}_o + \omega_o \times J_o \cdot \omega_o + R_{om} M_m
\]

Where \([M_i]_m\) is the projection of the reaction torque of the inner frame to the middle frame in the middle frame coordinate system. \([M_m]_o\) is the projection of the reaction torque of the outer frame of the middle frame in the outer frame coordinate system.

In the formula, the term of the inertial product is the unbalanced torque due to the uneven distribution of the mass of the frame.

4. Simulation Analysis

The three-axis stabilized platform servo control system uses speed-current dual-loop control, and the controller uses a classic controller(PID). The stable platform simulation model built by Simulink in Matlab is shown in Figure 2.
Figure 2. Simulation model of photoelectric stability platform Simulink.

The solid line box above Figure 2 is the system acceleration input and transfer model (See 3.1 for details). The three dashed boxes in Figure 2 are the outer frame model, the middle frame model and the inner frame model from left to right. There is an angular velocity transfer relationship between the frame models (See 2.2 for details).

4.1. Simulation without Mass Imbalance Torque
When there is no frame mass eccentricity and the inertia product term in each frame inertia tensor matrix is ignored. Set the controller parameters and set the carrier speed disturbance to be a sinusoidal signal with amplitude 1 m/s and frequency 2 Hz. Obtaining the boresight angle, that is, the system response is shown in Figure 3.

It can be seen from Fig. 3 that there is also a certain oscillation of the boresight angle due to the influence of the carrier disturbance. The magnitudes of the x, y, and z directions are $6.1 \times 10^{-5}, 8.2 \times 10^{-5}, 15 \times 10^{-5}$ (rad). The frequency is consistent with the carrier disturbance frequency.

4.2. Simulation in the Presence of Unbalanced Moment Due to the Eccentricity of the Frame
The inertial product term in each frame inertia tensor matrix is ignored. Let the eccentricity of each frame be $[0.005, 0.005, 0.005]$ m, and the carrier velocity perturbation is a sinusoidal signal with amplitude of $1^\circ$/s and frequency of 2 Hz.

(1) Refer to the helicopter equipment parameters, only take the overload acceleration amplitude of 1.5g (gravity acceleration), the frequency is 10 Hz in the x direction, and the other settings are unchanged. The system response is shown in Figure 4.

It can be seen from Figure 4 that under the interference of the unbalanced torque, the angles in the x, y, and z directions of the boresight are respectively signals of a peak value of $0.7 \times 10^{-4}, 2.9 \times 10^{-4}, 4.9 \times 10^{-4}$ (rad).

(2) Only take the overload acceleration amplitude of 1.5g in the y direction, the frequency is 10 Hz. The other settings are unchanged. The system response is shown in Figure 5.

It can be seen from Figure 5 that under the disturbance of the unbalanced torque, the angles in the x, y, and z directions of the boresight are respectively signals of a peak of $1.4 \times 10^{-4}, 0.8 \times 10^{-4}, 2.5 \times 10^{-4}$ (rad).

(3) Take only the overload acceleration amplitude of 1.5g in the z direction, the frequency is 10 Hz, and the other settings are unchanged. The system response obtained by simulation is shown in Figure 6.
It can be seen from Figure 6 that under the interference of the unbalanced torque, the angles in the x, y, and z directions of the boresight are respectively signals of a peak value of $1.4 \times 10^{-4}$, $2 \times 10^{-4}$, $3.2 \times 10^{-4}$ (rad).

In summary, in the presence of frame eccentricity and overload acceleration, the angular error of the boresight is significantly increased compared to the result of no unbalanced torque added, which has a great impact on the accuracy and stability of the system. More serious will also cause system instability.

**Figure 3.** The angular response of the boresight under carrier disturbance.

**Figure 4.** Angle response of the boresight under disturbance and unbalanced torque.

**Figure 5.** Angle response of the boresight under carrier and unbalanced torque.
4.3. Simulation in the Presence of Unbalanced Torque Due to Uneven Distribution of Frame Mass

It is assumed that there is no mass eccentricity in each frame, but there is an inertial product term in each frame inertia tensor matrix. The carrier rate perturbations are sinusoidal signals with amplitude $1^\circ/s$ and frequency 2 Hz, and other settings are unchanged. The system response obtained by simulation is shown in Figure 7.

![Figure 6](image1.png)

**Figure 6.** Angle response of the boresight under carrier and unbalanced torque.

![Figure 7](image2.png)

**Figure 7.** Angle response of the boresight under carrier and unbalanced torque.

It can be seen from Figure 7 that under the disturbance of the unbalanced torque, the angles of the boresight x, y, and z directions are respectively $-6.4 \times 10^{-5}, 8.2 \times 10^{-5}, 1.5 \times 10^{-4}$ (rad), and the frequency is consistent with the carrier disturbance frequency.

Compared with the boresight angle without adding unbalanced torque interference, it can be seen that the unbalanced torque generated by the frame due to uneven mass distribution has little influence on the boresight angle Therefore, to a certain extent, the unbalanced torque of the frame due to uneven mass distribution can be ignored.

5. Conclusions

In this paper, Simulink is used to model the simulation of the integrated three-axis three-frame photoelectric stability platform to explore the impact of mass imbalance on the accuracy and stability of the platform. The simulation results show that:

(1) When the platform is only subjected to the mass imbalance torque due to the eccentricity, the boresight angle has a large oscillation, which affects the accuracy and stability of the platform.
(2) When the platform is only subjected to mass imbalance torque due to uneven mass distribution, the boresight angle is less affected by it and has less influence on the accuracy and stability of the platform. Therefore, the use of frame eccentricity should be avoided during the use of photoelectric stabilization platforms. However, in the actual manufacturing assembly process, the eccentricity cannot be avoided, and the position of the center of mass needs to be adjusted by the counterweight to eliminate the existence of the eccentricity and improve the accuracy and stability of the stable platform.

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