Enhancing the kinematic quality of a single-axis stabilizing platform on a high-speed spinning-body aircraft

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Received 20 Apr. 2025; Revised 16 Jun. 2025; Accepted 20 Sep. 2025; Published 2 Oct. 2025.
DOI: https://doi.org/10.54939/1859-1043.j.mst.106.2025.10-17

ABSTRACT

Within the orientation system, a single-axis stabilizing platform is employed to mitigate the effects of high-speed aircraft body rotation on the sensors. To analyze its kinematic characteristics, this paper develops a dynamic model of the stabilizing platform's motion. Misalignment between the platform's axis and the rotational axis of the spinning-body aircraft introduces disturbance components that affect stabilization quality. This paper proposes a solution to reduce platform oscillations by employing a viscous vibration absorber. Simulation results using MATLAB Simulink clearly demonstrate the effectiveness of this approach.

Keywords: Stabilizing platform; Attitude determination; Spinning aircraft; Vibration absorber.

1. INTRODUCTION

During the control process of a single-channel spinning-body aircraft, information about the aircraft's roll angle around its longitudinal axis is required. Typically, a three-degree-of-freedom gyroscope is used to determine the roll angle [5, 7–9]. However, this device is often large and costly. Theoretically, angular rate gyroscopes can be used to determine the roll angle. Yet, to ensure stable flight, spinning-body aircraft often rotate at high speeds, which can exceed the measurement range of angular rate gyroscopes. As a result, for high-speed spinning-body aircraft, using an angular rate gyroscope rigidly attached to the body is not a viable solution for roll angle determination.

To address this issue, some studies have proposed the use of a single-axis stabilizing platform [1–4]. In this approach, an inertial sensor unit is mounted on a single-axis stabilizing platform aligned with the spinning-body aircraft's rotational axis. The platform's rotational speed is significantly lower than that of the aircraft. The aircraft's attitude angles are determined by measuring the stabilizing platform's attitude angles and its relative rotation with respect to the aircraft. The attitude angles of the stabilizing platform are obtained through an integration algorithm applied to signals from gyroscopes. Consequently, the accuracy of the attitude determination system depends on the kinematic characteristics of the stabilizing platform. To ensure high-precision attitude determination, the stabilizing platform must be stabilized to maintain minimal rotational speed and angular displacement.

When the spinning-body aircraft undergoes spinning motion, friction at the platform's bearings induces rotational movement of the platform. Previous studies [1–4] have suggested that manufacturing the platform with a certain level of eccentricity can help reduce its rotational speed and angular displacement. However, installation misalignment between the platform's rotational axis and the aircraft's rotational axis inevitably exists. This misalignment generates additional disturbance torques. This paper investigates the impact of installation errors on the kinematic characteristics of the single-axis stabilizing platform on a spinning-body aircraft and proposes a solution to mitigate these effects. Specifically, a viscous damper is proposed to suppress the oscillatory behavior of the platform base caused by misalignment and dynamic disturbances, thereby enhancing the platform's overall stability.

2. DYNAMICS OF THE SINGLE-AXIS STABILIZING PLATFORM MOTION

In the case where the rotational axis of the stabilizing platform coincides with the spinning-body aircraft's rotational axis, the spinning motion of the spinning-body aircraft affects the stabilizing platform only through friction at the bearings. However, in practical installations, there is always some degree of misalignment between the platform's axis and the spinning-body aircraft's rotational axis. This misalignment generates a centrifugal force acting on the platform's center of mass, induced by the spinning-body aircraft's rotational motion. For spinning-body aircraft, the angular velocity and angular acceleration components in directions perpendicular to the longitudinal axis are significantly smaller than the spinning-body aircraft's spinning angular velocity. As a result, disturbances caused by these components are much smaller compared to those induced by the spinning-body aircraft's spinning motion. Therefore, in this study, we assume that the spinning-body aircraft's rotational axis is parallel to the stabilizing platform's axis.

Figure 1 illustrates the model of the single-axis stabilizing platform mounted on a spinning-body aircraft.

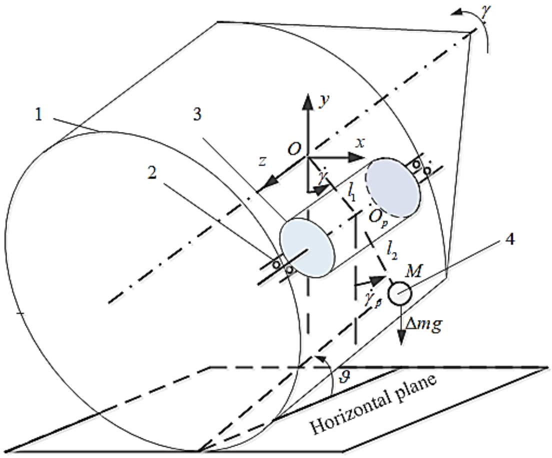

Figure 1. *Single-axis stabilizing platform on a spinning-body aircraft.*

In this setup, the spinning-body aircraft (1) rotates around its own axis with an angular velocity $\dot{\gamma}$, and a single-axis stabilizing platform is mounted on it. The platform's axis is kept parallel to the spinning-body aircraft's rotational axis using ball bearings (2). The misalignment between the platform's axis and the spinning-body aircraft's rotational axis is denoted by l_1.

For the sake of analytical convenience, we assume that the stabilizing platform consists of a cylindrical mass with mass *m* and radius *r*, along with an additional weight Δm rigidly attached to the cylinder. This weight Δm is positioned at a radial distance l_2 from the platform's rotational axis.

The coordinate system has its origin *O* at the aircraft's center of mass. The *x*-axis is parallel to the horizontal plane and perpendicular to the spinning-body aircraft's longitudinal axis, the y-axis lies in the vertical plane perpendicular to the spinning-body aircraft's longitudinal axis, and the *z*-axis forms a right-handed coordinate system with *x* and *y*. The point O_P represents the center of mass of the cylindrical stabilizing platform. A plane perpendicular to the spinning-body aircraft's rotational axis passes through O_P and the center of mass of the weight *M*.

The variables $\gamma, \dot{\gamma}$ represent the rotational angle and angular velocity of the aircraft, respectively, while $\gamma_p, \dot{\gamma}_p$ represent the rotational angle and angular velocity of the stabilizing platform in space. The parameter ϑ denotes the aircraft's pitch angle.

Now, consider an infinitesimal mass element dm_i on the stabilizing platform, located at a radial distance l_{2i} from the platform's axis. This mass element is positioned at an angular displacement γ_{pi} from the vertical direction. The coordinates of dm_i in the coordinate system *Oxyz* can be expressed using the following equations:

$$\begin{aligned} x_{pi} &= l_1 \sin\gamma + l_{2i} \sin\gamma_{pi} \\ y_{pi} &= -l_1 \cos\gamma - l_{2i} \cos\gamma_{pi} \end{aligned} \tag{1}$$

Based on equation (1), the velocity of the application point can be determined using the following expression:

$$\begin{aligned} \dot{x}_{pi} &= \dot{\gamma} l_1 \cos\gamma + l_{2i} \dot{\gamma}_{pi} \cos\gamma_{pi} \\ \dot{y}_{pi} &= \dot{\gamma} l_1 \sin\gamma + \dot{\gamma}_{pi} l_{2i} \sin\gamma_{pi} \end{aligned} \tag{2}$$

From equation (2), the acceleration of the application point can be derived.

$$\begin{aligned} \ddot{x}_{pi} &= \ddot{\gamma} l_1 \cos\gamma - \dot{\gamma}^2 l_1 \sin\gamma + \ddot{\gamma}_{pi} l_{2i} \cos\gamma_{pi} - \dot{\gamma}_{pi}^2 l_{2i} \sin\gamma_{pi} \\ \ddot{y}_{pi} &= \ddot{\gamma} l_1 \sin\gamma + \dot{\gamma}^2 l_1 \cos\gamma + \ddot{\gamma}_{pi} l_{2i} \sin\gamma_{pi} + \dot{\gamma}_{pi}^2 l_{2i} \cos\gamma_{pi} \end{aligned} \tag{3}$$

The aircraft rotates around its axis at a high velocity, so in this problem, it can be assumed that the *z*-axis remains stationary in space. If the Earth's rotation is neglected, the coordinate system can be considered an absolute reference frame.

Thus, for each point on the stabilizing platform corresponding to a mass element dm_i, there are two acceleration components perpendicular to the platform's rotational axis, which are determined using equation (3). The motion of the mass element dm_i in this case is equivalent to external forces acting along the *z*-axis, with magnitudes proportional to the product of the mass and the corresponding acceleration.

From this, the moment acting on the mass dm_i about the rotational axis of the stabilizing platform can be calculated using the following equation.

$$x_{pi} dm_i \ddot{y}_{pi} - y_{pi} dm_i \ddot{x}_{pi} = -dm_i[\ddot{\gamma} l_1 l_{2i} \cos(\gamma - \gamma_{pi}) - \dot{\gamma}^2 l_1 l_{2i} \sin(\gamma - \gamma_{pi})]$$

For each infinitesimal mass element dm_i on the cylindrical stabilizing platform, there exists a symmetric point around the platform's rotational axis. Consequently, the mass element dm_i at that point will generate a moment given by: $-dm_i[\ddot{\gamma} l_1 l_{2i} \cos(\gamma - \gamma_{pi} + \pi) - \dot{\gamma}^2 l_1 l_{2i} \sin(\gamma - \gamma_{pi} + \pi)]$. Therefore, for the cylindrical part of the stabilizing platform, the total moment generated by the aircraft's rotational motion acting on the platform along its axis is zero. If the additional mass *M* is considered to be small in size with mass Δm, then when the aircraft rotates around its longitudinal axis with angular velocity $\dot{\gamma}$ and angular acceleration $\ddot{\gamma}$, it will generate a moment acting on the platform given by: $-\Delta m[\ddot{\gamma} l_1 l_2 \cos(\gamma - \gamma_p) - \dot{\gamma}^2 l_1 l_{2i} \sin(\gamma - \gamma_p)]$.

Therefore, based on Newton's second law, the rotational motion equation of the stabilizing platform can be expressed as follows:

$$J_p \ddot{\gamma}_p = -\mu_{kk} \dot{\gamma}_p - \Delta m g l_2 \sin\gamma_p \cos\vartheta - \Delta m[\ddot{\gamma} l_1 l_2 \cos(\gamma - \gamma_p) - \dot{\gamma}^2 l_1 l_2 \sin(\gamma - \gamma_p)] + M^{ms} \tag{4}$$

Here, J_p represents the moment of inertia of the platform about its rotational axis; μ_{kk} is the damping coefficient due to air viscosity; the term $\Delta m g l_2 \sin\gamma_p \cos\vartheta$ represents the moment acting on the platform's rotational axis due to gravitational force; and M^{ms} denotes the frictional moment generated at the platform's bearings. Based on the obtained equation, it can be observed that the aircraft's angular acceleration and angular velocity influence the rotational motion of the platform.

The component dependent on the aircraft body rotational acceleration $\Delta m\ddot{\gamma}l_1l_2\cos(\gamma-\gamma_p)$ and the component dependent on the square of the aircraft's rotational velocity $\Delta m\dot{\gamma}^2l_1l_2\sin(\gamma-\gamma_p)$ can be considered as a disturbance factor in the rotational motion of the platform. The magnitudes of these components are proportional to the misalignment between the stabilizing platform's rotational axis and the aircraft's rotational axis l_1.

If the platform's rotational angle is assumed to have a small amplitude, then $\gamma >> \gamma_p$, meaning that the aforementioned disturbance components will act at a frequency equal to the aircraft's rotational frequency.

In the case where the angle γ_p is small, then $\Delta mgl_2\sin\gamma_p\cos\vartheta \approx (\Delta mgl_2\cos\vartheta)\gamma_p$, the system's natural frequency is given by $\sqrt{\frac{\Delta mgl_2\cos\vartheta}{J_h}}$. Since the damping coefficient μ_{kk}, due to air viscosity, is small, the stabilizing platform exhibits significant resonance characteristics. Additionally, based on equation (4), it can be observed that the external moment acting on the stabilizing platform includes a component dependent on the axis misalignment l_1. In the external moment components, there are terms associated with the aircraft's angular acceleration and rotational velocity, which vary at a frequency equal to the aircraft's rotational frequency. Therefore, if the platform's natural frequency is close to the aircraft's rotational frequency, the effects of resonance will be significant.

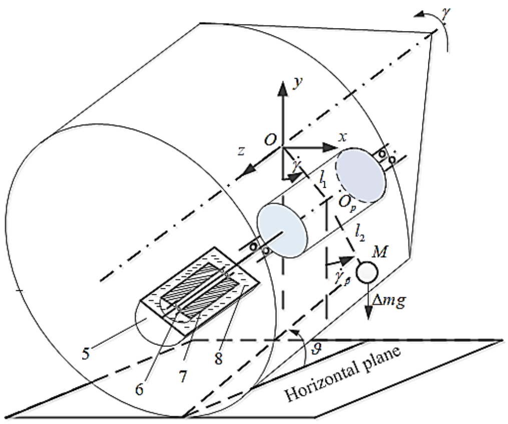

Figure 2. *Model of a single-axis stabilizing platform with an integrated vibration absorber.*

A simple solution to mitigate resonance effects is to increase the damping of the system. The following section examines a method to enhance the damping coefficient of the stabilizing platform's rotational motion. In mechanical systems, viscous dampers are commonly used to eliminate resonance effects [6].

The model of the stabilizing platform incorporating a viscous damper is shown in Figure 2. The damping device consists of a casing (5), a damping mass (7), which is mounted on bearings (6). To introduce viscosity, the damping mass (7) is immersed in a liquid (8) and can rotate around the bearings (6). The axis of rotation of the damping mass (7) coincides with the axis of rotation of the stabilizing platform.

The equations describing the motion of the single-axis stabilizing platform with the damper are given as follows:

$$\begin{aligned}&\ddot{\gamma}_pJ_p+\mu_h(\dot{\gamma}_p-\dot{\gamma}_h)+\Delta mgl_2\sin\gamma_p\cos\vartheta=-\Delta m[\ddot{\gamma}l_1l_2\cos(\gamma-\gamma_p)-\dot{\gamma}^2l_1l_2\sin(\gamma-\gamma_p)]+M^{ms}\\&J_h\ddot{\gamma}_h=\mu_h(\dot{\gamma}_p-\dot{\gamma}_h)\end{aligned} \quad (5)$$

where $\dot{\gamma}_h$ is the absolute angular velocity of the damping element, J_h is the moment of inertia of the damping element and μ_h is the viscous damping coefficient of the damping element.

From the second equation in system (5), $\dot{\gamma}_h$ can be expressed in terms of $\dot{\gamma}_p$. Substituting this expression into the first equation of system (5) results in the following differential equation describing the motion of the stabilizing platform:

$$J_p\ddot{\gamma}_p + \frac{\mu_h J_h s}{J_h s + \mu_h}\dot{\gamma}_p + \Delta m g l_2 \sin\gamma_p \cos\vartheta = -\Delta m[\ddot{\gamma} l_1 l_2 \cos(\gamma - \gamma_p) - \dot{\gamma}^2 l_1 l_2 \sin(\gamma - \gamma_p)] + M^{ms} \quad (6)$$

where *s* is the Laplace operator.

From the obtained equation, it can be observed that the system exhibits a damping component with a coefficient $\frac{\mu_h J_h s}{J_h s + \mu_h}$. The selection of parameters for the viscous damper significantly affects the stability quality of the single-axis stabilizing platform. In the case where the viscous friction coefficient μ_h is large, the equation of motion for the stabilizing platform takes the following form:

$$\ddot{\gamma}_p(J_p + J_h) + \Delta m g l_2 \sin\gamma_p \cos\vartheta = -\Delta m[\ddot{\gamma} l_1 l_2 \cos(\gamma - \gamma_p) - \dot{\gamma}^2 l_1 l_2 \sin(\gamma - \gamma_p)] + M^{ms} \quad (7)$$

At this point, the damper acts as if an additional mass with a moment of inertia J_h is coaxially attached to the stabilizing platform. In this case, the damper does not effectively suppress oscillations.

For a viscosity coefficient satisfying $|J_h s| >> \mu_h$, the system of equations (7) can be approximated as follows:

$$J_p\ddot{\gamma}_p + \mu_h\dot{\gamma}_p + \Delta m g l_2 \sin\gamma_p \cos\vartheta = -\Delta m[\ddot{\gamma} l_1 l_2 \cos(\gamma - \gamma_p) - \dot{\gamma}^2 l_1 l_2 \sin(\gamma - \gamma_p)] + M^{ms} \quad (8)$$

In this case, the damper introduces damping into the single-axis stabilizing platform system, with the damping coefficient being equal to its own damping coefficient. This characteristic helps suppress oscillations of the stabilizing platform when the aircraft undergoes body rotation. Assuming the stabilizing platform is well stabilized, resulting in a small platform rotation angle, the above equation can be rewritten in the following form:

$$J_p\ddot{\gamma}_p + \mu_h\dot{\gamma}_p + \Delta m g l_2 \gamma_p \cos\vartheta = -\Delta m[\ddot{\gamma} l_1 l_2 \cos(\gamma) - \dot{\gamma}^2 l_1 l_2 \sin(\gamma)] + M^{ms} \quad (9)$$

The first two terms on the right-hand side of the above differential equation depend on the rotational motion characteristics of the aircraft. For a spinning-body aircraft, the squared angular velocity term is significantly larger than the angular acceleration term, allowing the first term to be neglected. Thus, the installation error of the stabilizing platform generates a harmonic disturbance moment with a frequency equal to the aircraft's rotational frequency, while its magnitude is proportional to the product of the squared angular velocity and the installation misalignment.

3. SIMULATION ANALYSIS

To simulate and analyze the dynamic characteristics of the stabilizing platform with a viscous vibration absorber as described in equation (5), a simulation model is developed. The simulation diagram is shown in figure 3.

Parameters of the elements in the simulation model:

The cylindrical body of the platform has a mass of $m = 0,3\ kg$ and a radius of $r = 0,010\ m$. The added mass is $\Delta m = 0,01\ kg$, with an offset of from the platform's rotational axis $l_2 = 0,02\ m$;

The installation misalignment between the stabilizing platform axis and the aircraft's rotational axis is $l_1 = 0,003m$;

The frictional moment at the platform's bearings is $M^{ms} = 6.10^{-4} N.m$, and the air damping coefficient is $\mu_{kk} = 0$;

The pitch angle of the aircraft is $\vartheta = 30^0$;

The aircraft's angular acceleration follows the equation: $\ddot{\gamma} = 60\frac{rad}{s^2}$ with $t \le 1s$ and $\ddot{\gamma} = 0\frac{rad}{s^2}$ with $t > 1s$;

The moment of inertia of the vibration absorber is $J_h = 10^{-5} kg.m^2$;

In the simulation model, the damping coefficient of the absorber μ_h is varied to evaluate the dynamic characteristics of the stabilizing platform motion.

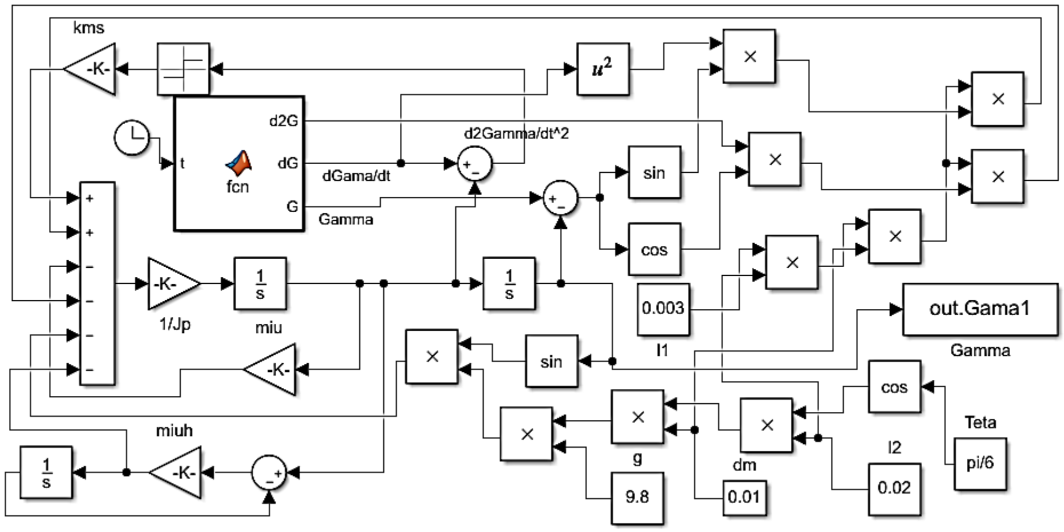

Figure 3. *Simulation diagram of the stabilizing platform motion.*

Figures 4 and 5 illustrate the variations in the angular velocity and rotation angle of the stabilizing platform for different damping coefficients of the vibration absorber.

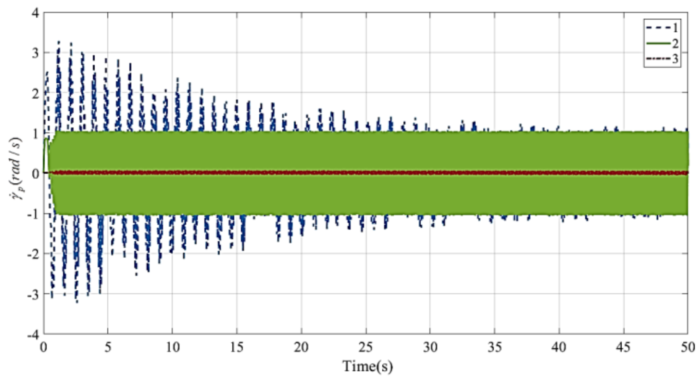

Figure 4. *Angular velocity of the stabilizing platform for different viscous coefficients of the vibration absorber.*

In figure 4, curve 1 represents the angular velocity characteristics of the stabilizing platform with $\mu_h = 5.10^{-6} N.s.m$. When the viscosity increases to $\mu_h = 5.10^{-4} N.s.m$, the velocity variation is shown in curve 2. Curve 3 illustrates the velocity variation characteristics of the platform with $\mu_h = 5.10^{-2} N.s.m$.

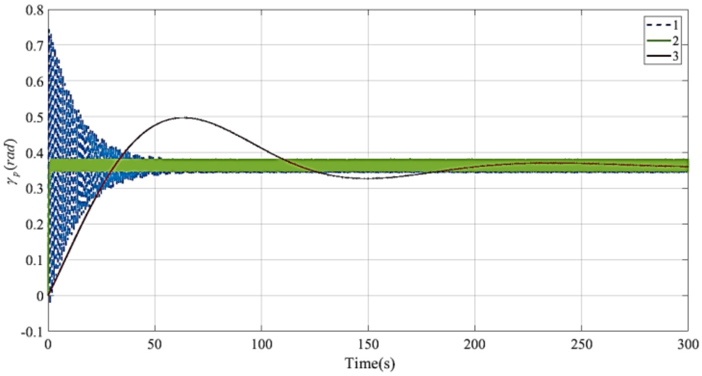

Figure 5. *Rotation angle of the stabilizing platform for different viscous coefficients of the vibration absorber.*

In figure 5, curve 1 represents the variation of the angular of the stabilizing platform with $\mu_h = 5.10^{-6}\,N.s.m$. When the viscosity of the absorber increases to $\mu_h = 5.10^{-4}\,N.s.m$, the transient process of the platform's rotation angle is shown in curve 2. With $\mu_h = 5.10^{-2}\,N.s.m$, the variation of the platform's rotation angle is illustrated in curve 3.

Simulation results indicate that when the damping coefficient of the absorber is small, the aircraft's rotational motion induces high-frequency, large-amplitude forced oscillations in the stabilizing platform. However, when a high-viscosity absorber is used, the oscillatory effects caused by the aircraft's rotation are significantly reduced. Additionally, it is evident that for different viscosity coefficients, the stabilizing platform oscillates around a specific angular position. This characteristic arises from the system consistently experiencing a frictional force in the same direction as the aircraft's rotation with a constant magnitude. Thus, installation misalignment is the primary cause of forced disturbance torque, leading to oscillations in the stabilizing platform. The magnitude of this torque is proportional to the installation misalignment between the stabilizing platform's axis and the aircraft's rotational axis. To mitigate oscillatory motion in the stabilizing platform, a dynamic vibration absorber is employed.

4. CONCLUSIONS

The paper develops a dynamic model for the motion of a stabilizing platform mounted on a spinning-body aircraft. The obtained model reveals that installation misalignment generates a disturbance torque component that varies approximately sinusoidally with a frequency equal to the aircraft's rotational frequency and an amplitude proportional to the square of the rotational speed and the misalignment magnitude. This effect significantly increases both the angular velocity and the rotation angle of the stabilizing platform. To enhance the dynamic performance of the stabilizing platform, the paper proposes the application of a viscous damping absorber. The absorber increases damping and suppresses oscillations in the stabilizing platform. Simulation results obtained using MATLAB Simulink demonstrate the impact of installation misalignment on the platform's motion dynamics and validate the effectiveness of the proposed damping absorber in improving the platform's stability.

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TÓM TẮT

Nâng cao chất lượng động học của đế ổn định một trục trên thiết bị bay xoay thân tốc độ cao

Trong hệ thống xác định tư thế, đế ổn định một trục được sử dụng để giảm thiểu ảnh hưởng của chuyển động quay tốc độ cao của thân thiết bị bay lên các cảm biến. Để phân tích các đặc tính động học của nó, bài báo này xây dựng một mô hình động lực học cho chuyển động của đế ổn định. Độ lệch giữa trục của đế ổn định và trục quay của thiết bị bay gây ra các thành phần nhiễu, ảnh hưởng đến chất lượng ổn định. Bài báo đề xuất một giải pháp nhằm giảm dao động của đế ổn định bằng cách sử dụng bộ giảm chấn dao động nhớt. Kết quả mô phỏng bằng MATLAB Simulink cho thấy rõ hiệu quả của phương pháp này.

Từ khóa: Đế ổn định; Xác định tư thế; Thiết bị bay xoay thân; Hấp thu rung.