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ROBUST ATTITUDE CONTROLLER AND FAULT DETECTION OF FLEXIBLE SATELLITE

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To ensure reliable and accurate flexible satellite operations, it is crucial to develop effective control schemes. This paper proposes an interesting PD controller and observer scheme for a flexible satellite. Specifically, a functional observer aimed to detect and mitigate actuator fault occurrences, complemented by an output feedback-based control system to effectively compensate for the satellite disturbances and vibrations. The controller achieves enhanced steady-state tracking accuracy by handling the satellite's flexible dynamics as disturbances. The convergence of tracking error and stability of the closed-loop system is ensured through Lyapunov analysis. The performance of the proposed control scheme is demonstrated numerically, which revealed significant improvements in satellite attitude control precision and stability against vibration issues with actuator faults.

1. INTRODUCTION

Over the past few years, numerous researchers have studied the vibration issue arising from satellites' flexible appendages, aiming to offer a resolution. This effort stems from the intricate nature of designing attitude controllers for spacecraft systems, which demands precision in attitude pointing and endurance to guarantee the success of space missions [1–3].

Early on, many researchers conducted extensive studies on vibration suppression problems [4,5] and considered the optimal attitude control scheme for flexible spacecraft. More robust control methods were developed to improve performance in the presence of structural vibrations. The sliding mode control (SMC) has been acknowledged as a practical design for the attitude control system [6,7]. However, the chattering phenomenon induced by the control switching has hindered its practical application. Consequently, alternative approaches such as adaptive control [8,9], a linear quadratic regulator (LQR) [10], and the back-stepping approach [11,12] have been explored. The adaptive control method has emerged as a solution to address the challenges posed by complex variant dynamics. As a result, it is widely favored in the aerospace domain for tackling vibration-related issues.

Moreover, in [13], the problem of tracking attitude trajectory is addressed by utilizing LMI-based gain-scheduled H-infinity control.

Additionally, the engineering test satellites (ETS-VI) and (ETS-VIII), launched by the Japanese aerospace exploration agency, served as platforms for the development and validation of various dynamic H∞ output feedback controllers [14,15], showcasing their performance capabilities. The input shaping approach and its applications have experienced considerable growth in effectively reducing vibrations in flexible spacecraft [16,17]. However, the control methods mentioned above rely on the accuracy of the dynamic system model or treat disturbances as bounded norms, resulting in a limited utilization of available disturbance information.

Disturber observer-based control (DOBC) is a promising strategy that has garnered significant attention for effective disturbance attenuation. Its extensions have been successfully implemented in robots and hard missiles [18,19]. In the context of flexible satellites, a disturbance observer approach has been proposed [20,22], enabling the estimation and adequate compensation of disturbances through feedforwards.

Nonetheless, conventional attitude control schemes, which do not account for actuator faults, lack the robustness needed to control a flexible spacecraft experiencing faults effectively. To ensure satisfactory performance, several fault tolerant control (FTC) strategies have been developed for the simultaneous tracking and control of flexible spacecraft while suppressing vibrations [23,24].

This paper introduces a novel PD controller and observer scheme to mitigate actuator faults. A functional observer is devised to detect fault occurrences, while an output feedback-based control is designed to address vibrations and disturbances. The controller treats flexible dynamics as disturbances, enhancing steady-state tracking accuracy. The Lyapunov analysis method guarantees the convergence of tracking error and stability of the closed-loop system. Ultimately, the results demonstrate the feasibility and efficiency of the proposed controller, enhancing the satellite attitude control system and enabling high precision and stability in combating vibration issues.

2. MATERIAL AND METHODS

This study examines a three-axis flexible satellite, as shown in Fig. 1. A typical flexible spacecraft consists of a rigid body and several flexible appendages, such as large solar panels and antennas.

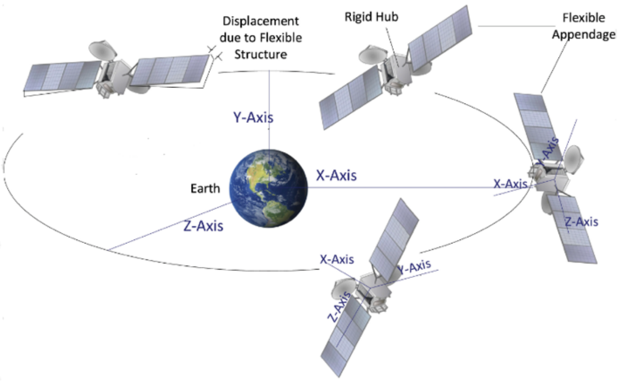

Fig. 1 – Spacecraft with flexible appendages. [25].

2.1 MATHEMATICAL MODEL OF SATELLITE ATTITUDE

The rotational dynamics equations of the spacecraft, incorporating flexible appendages, are described as follows: [26,27]:

$$\mathbf{J}\mathrm{d}\mathbf{w} = -\mathbf{w}^{\times}\mathbf{J}\mathbf{w} + \mathbf{u} + \mathbf{D}. \tag{1}$$

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$$\mathrm{d}^2\mathbf{H} + 2\mathbf{G}\mathrm{d}\mathbf{H} + \mathbf{A}^2\mathbf{H} + \mathbf{C}\mathrm{d}\mathbf{w} = 0, \tag{2}$$

where $\mathbf{J} \in R^{3\times3}$ is the inertia moment of the satellite, $\mathbf{w} = (w_1 \quad w_2 \quad w_3)^T$ is the angular rate, $\mathbf{H} \in R^3$ is the model coordinate of the flexible appendages, $\mathbf{C} \in R^{3\times3}$is the coupling matrix, $\mathbf{G} = \mathrm{diag}[G_1, G_2, G_3]$ is the damping ratio, $\mathbf{A}$ is the model frequency, $\mathbf{u} \in R^3$ is the control torque, and $\mathbf{D} \in R^3$ represents the disturbance induced by the vibration of the flexible appendages.

Denote $[a^\times]$ an operator such that [28].

$$[\mathbf{a}^\times] = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_2 \\ -a_2 & a_1 & 0 \end{bmatrix}. \tag{3}$$

The kinematic attitude equations, employing attitude quaternions, are applied as follows:

$$\mathrm{d}\mathbf{q}_v = \tfrac{1}{2}(\mathbf{q}_v^\times + q_0\mathbf{I}_3)\mathbf{w}, \tag{4}$$

$$\mathrm{d}q_0 = -\tfrac{1}{2}\mathbf{q}_v^{\mathrm{T}}\mathbf{w}, \tag{5}$$

where $\mathbf{I_3}$ is a three-unit matrix, $\mathbf{q}_v = [q_1 \quad q_2 \quad q_3]^{\mathrm{T}}$ is the vector part of $\mathbf{q}$, q_0 the unit quaternion of the satellite body coordinate system, and $\mathbf{q} = [q_0, \mathbf{q}_v]^{\mathbf{T}}$.

Let $\mathbf{q}_e = [\mathbf{q}_{ve}, \mathbf{q}_{0e}]^{\mathbf{T}}$ denote the relative attitude error from a desired reference frame to the body-fixed reference frame of the satellite. Consequently, we obtain:

$$\mathbf{q}_{\boldsymbol{e}} = \mathbf{q} \otimes \mathbf{q}_d^{-1}, \tag{6}$$

where $\mathbf{q}_d^{-1}$ is the inverse of the desired quaternion and $\otimes$ is the quaternion multiplication operator. Therefore, the relative attitude error is obtained by:

$$\begin{bmatrix} \mathrm{d}\mathbf{q}_{ve} \\ \mathrm{d}\mathbf{q}_{0e} \end{bmatrix} = \tfrac{1}{2}\begin{bmatrix} \mathbf{q}_{0v}\mathbf{I}_{3\times3} + (\boldsymbol{q}_{ve}^\times) \\ -\mathbf{q}_{ve}^{\mathrm{T}} \end{bmatrix}\omega_e(t), \tag{7}$$

and

$$\mathbf{w}_e = \mathbf{w} - \mathbf{w}_d, \tag{8}$$

where $\mathbf{w}_d$ represents the desired angular velocity of the body, which is assumed to be zero for our purposes. Therefore,

$$\mathbf{w}_d = 0 \rightarrow \mathbf{w}_e = \mathbf{w}.$$

Hence, the rate of angular velocity can be obtained as follows:

$$\mathrm{d}\mathbf{w}_e = \mathrm{d}\boldsymbol{w} = -\mathbf{J^{-1}}(\mathbf{w}^\times)\mathbf{J}\mathbf{w} + \mathbf{J}^{-1}\mathbf{u} + \mathbf{J}^{-1}\mathbf{D}. \tag{9}$$

2.2 DISTURBANCE OBSERVER DESIGN

Assumption: The "equivalent" disturbance $\boldsymbol{d}$ is slowly varying and limited. Therefore, $\dot{\boldsymbol{d}} \approx 0$ is reasonable.

To estimate the disturbance of system (1), we formulate the disturbance observer as follows:

$$\begin{cases} \widehat{\mathbf{D}} = \mathbf{z} + \mathbf{L}\mathbf{w}, \\ \mathrm{d}\mathbf{z} = -\mathbf{L}(-\mathbf{J}^{-1}(\mathbf{w}^\times(\mathbf{J}\mathbf{w}) + \mathbf{J}^{-1}\mathbf{u}) - \mathbf{L}\mathbf{J^{-1}}(\mathbf{z} + \mathbf{L}\mathbf{w}), \end{cases} \tag{10}$$

where $\widehat{\boldsymbol{D}}$ is the estimation of the disturbance, $\mathbf{d}$, and $\mathbf{L}$ is the matrix observer gain.

Denoting $\mathbf{D}_e$ as the disturbance observer error, that:

$$\mathrm{d}\mathbf{D}_e = \mathrm{d}\mathbf{D} - \mathrm{d}\widehat{\mathbf{D}} \approx -\mathrm{d}\widehat{\mathbf{D}} = -\mathrm{d}\mathbf{z} - \mathbf{L}\mathrm{d}\mathbf{w}, \tag{11}$$

Considering the practical context of flexible vibration, it is necessary to design an appropriate gain $\boldsymbol{L}$ to ensure convergence of the estimation error to the origin $\mathbf{D}_e \rightarrow 0$.

Choosing a candidate Lyapunov function as:

$$V_1 = \tfrac{1}{2}\mathbf{D}_e^{\mathrm{T}}\mathbf{D}_e > 0. \tag{12}$$

By computing the derivative of (12), we get

$$\mathrm{d}V_1 = \mathbf{D}_e^{\mathrm{T}}\mathrm{d}\mathbf{D}_{\boldsymbol{e}} = \mathbf{D}_e^{\mathrm{T}}(-\mathrm{d}\mathbf{z} - \boldsymbol{L}\mathrm{d}\mathbf{w}). \tag{13}$$

Substituting (10) into (13) gives

$$\mathrm{d}V_1 = \mathbf{D}_e^{\mathrm{T}}\mathbf{L}\big(-\mathbf{J}^{-1}\big(\mathbf{w}^\times(\mathbf{J}\mathbf{w})\big) + \mathbf{J}^{-1}\mathbf{u} - \mathrm{d}\mathbf{w}\big) + \mathbf{D}_e^{\mathrm{T}}\mathbf{L}\mathbf{J^{-1}}\,\widehat{\mathbf{D}} \tag{14}$$

According to the (2), the (14) can be rewritten as follows

$$\begin{aligned} \mathrm{d}V_1 &= -\mathbf{D}_e^{\mathrm{T}}\mathbf{L}\mathbf{J}^{-1}\mathbf{D} + \mathbf{D}_e^{\mathrm{T}}\mathbf{L}\mathbf{J}^{-1}\widehat{\mathbf{D}} = \\ &= -\mathbf{D}_e^{\mathrm{T}}\mathbf{L}\mathbf{J}^{-1}\mathbf{D}_e. \end{aligned} \tag{15}$$

As $\mathbf{J}^{-1}$ and $\mathbf{L}$ are positive define matrices, hence:

$$\mathrm{d}\boldsymbol{V_1} < 0. \tag{16}$$

We can deduce that the error $\mathbf{d}_e$ converges to the origin.

2.3 COMPOSITE CONTROL DESIGN

In this section, a composite controller based on the PD and DO is designed to counteract the effect of the vibration of the spacecraft. To accomplish this purpose, we will show the controller law as follows:

$$\mathbf{u} = \mathbf{w}^\times\mathbf{J}\mathbf{w} - \mathbf{K}_1\mathbf{w} - \mathbf{K}_2\mathbf{q}_v - \widehat{\mathbf{D}} \tag{17}$$

where $\mathbf{D}$ and $\mathbf{K}$ are positive constants.

To demonstrate the stability of the system, the following Lyapunov candidate function is selected

$$V_2 = \tfrac{1}{2}\mathbf{w}^{\mathrm{T}}\mathbf{K}_2{}^{-1}\mathbf{J}\mathbf{w} + 2(1 - q_0) + \tfrac{1}{2}\mathbf{D}_e^{\mathrm{T}}\mathbf{D}_e. \tag{18}$$

Hence $\dot{V}_2$ is expressed by:

$$\begin{aligned} \mathrm{d}V_2 &= \mathbf{w}^{\mathrm{T}}\mathbf{K}_2{}^{-1}\mathbf{J}\mathrm{d}\mathbf{w} - 2\mathrm{d}q_0 + \mathbf{D}_e^{\mathrm{T}}\mathrm{d}\boldsymbol{D}_e = \\ &= \mathbf{w}^{\mathrm{T}}\mathbf{K}_2{}^{-1}(-\mathbf{w}^\times\mathbf{J}\mathbf{w} + \mathbf{u} + \mathbf{d}) - 2\mathrm{d}q_0 + \mathbf{D}_e^{\mathrm{T}}\mathrm{d}\mathbf{D}_e. \end{aligned} \tag{19}$$

Substituting (17) into (19) yields

$$\mathrm{d}V_2 = -\boldsymbol{w}^{\mathrm{T}}\boldsymbol{K}_2{}^{-1}\boldsymbol{K}_1\boldsymbol{w} + \omega^{\mathrm{T}}\boldsymbol{K}_2{}^{-1}\boldsymbol{D}_{\boldsymbol{e}} + \boldsymbol{w}^{\mathrm{T}}\boldsymbol{q}_{\boldsymbol{v}} - 2\dot{q}_0 + \boldsymbol{D}_e^{\mathrm{T}}\mathrm{d}\boldsymbol{D}_e. \tag{20}$$

Based on (5), (20) is given as follows

$$\mathrm{d}V_2 = -\boldsymbol{w}^{\mathrm{T}}\boldsymbol{K}_2{}^{-1}\boldsymbol{K}_1\boldsymbol{w} + \boldsymbol{w}^{\mathrm{T}}\boldsymbol{K}_2{}^{-1}\boldsymbol{D}_e + \mathrm{d}\boldsymbol{V}_1. \tag{21}$$

Based on (17) and $\boldsymbol{D_e} \rightarrow 0$, we can infer that

$$\mathrm{d}V_2 < 0. \tag{22}$$

The negativeness of $\mathrm{d}V_2$ ensures the asymptotic stability of the system.

3. FAULT-TOLERANT ADAPTIVE BACKSTEPPING CONTROL DESIGN

The method aims to develop a controller capable of tolerating actuator faults. This controller design incorporates an adaptive Lyapunov approach, serving as an introduction to the adaptive PD controller. When actuator faults occur, the dynamic equation model is modified accordingly

$$\mathbf{J}\mathrm{d}\mathbf{w} = -\mathbf{w}^\times\mathbf{J}\mathbf{w} + \mathbf{u}_1 + \mathbf{D} + \mathbf{f}_a, \tag{23}$$

where $\mathbf{f}_a$ is the additive fault, and the estimated fault errors $\tilde{\mathbf{f}}_a = \hat{\mathbf{f}}_{\boldsymbol{a}} - \mathbf{f}_a$, where $\hat{\mathbf{f}}_a$ is the estimated additive fault, $\mathbf{u}_1$ is the proposed controller.

Lyapunov candidate function can be expressed as

$$V_3 = \tfrac{1}{2}\mathbf{w}^{\mathrm{T}}\mathbf{K}_2{}^{-1}\mathbf{J}\mathbf{w} + 2(1 - q_0) + \tfrac{1}{2}\mathbf{D}_e^{\mathrm{T}}\mathbf{D}_e + \tfrac{1}{2}\tilde{\mathbf{f}}_a^{\mathrm{T}}\Gamma^{-\mathbf{1}}\tilde{\mathbf{f}}_a, \tag{24}$$

where Γ must be a positive value in the design. The derivative is computed as,

$$dV_3 = \mathbf{w}^{\mathrm{T}}\mathbf{K}_2^{-1}\mathbf{J}d\mathbf{w} + 2\dot{q}_0 + \mathbf{D}_e^{\mathrm{T}}d\mathbf{D}_e + \tilde{\mathbf{f}}_a\boldsymbol{\Gamma}^{-1}d\hat{\mathbf{f}}_a, \quad (25)$$

$$dV_3 = \mathbf{w}^{\mathrm{T}}\mathbf{K}_2^{-1}(-\mathbf{w}^{\times}\mathbf{J}\mathbf{w} + \mathbf{u}_1 + \mathbf{D} + \mathbf{f}_a) - 2dq_0 + \mathbf{D}_e^{\mathrm{T}}d\mathbf{D}_e + \tilde{\mathbf{f}}_a\Gamma^{-1}d\hat{\mathbf{f}}_a \quad (26)$$

To ensure a negative derivative, we choose for the control $\mathbf{u}_1$ as outlined below:

$$\mathbf{u}_1 = \mathbf{w}^{\times}\mathbf{J}\mathbf{w} - \mathbf{K}_1\mathbf{w} - \mathbf{K}_2\mathbf{q}_v - \hat{\mathbf{d}} - \hat{\mathbf{f}}_a. \quad (27)$$

Substituting (23), (27) into (26) yields

$$dV_3 = dV_2 + \mathbf{w}^{\mathrm{T}}\mathbf{K}_2^{-1}\tilde{\mathbf{f}}_a + \tilde{\mathbf{f}}_a\boldsymbol{\Gamma}^{-1}d\hat{\mathbf{f}}_a. \quad (28)$$

Finally, we get

$$dV_3 = dV_2 + \tilde{\mathbf{f}}_a\left[-\mathbf{w}^{\mathrm{T}}\mathbf{K}_2^{-1} + \boldsymbol{\Gamma}^{-1}d\hat{\mathbf{f}}_a\right]. \quad (29)$$

The expressions describing the updated laws for the estimated faults are as follows:

$$d\hat{\mathbf{f}}_a = \boldsymbol{\Gamma}\mathbf{w}^{\mathrm{T}}\mathbf{K}_2^{-1}. \quad (30)$$

Subsequently, we can ensure that dV_3 thereby establishing the uniform asymptotic stability of systems under fault.

4. SIMULATION RESULTS

In this section, we demonstrate the disturbance mitigation capability and robust performance of the proposed composite control algorithm for flexible spacecraft through numerical simulations. We present the response of attitude angle and angular rate using both the PD and the proposed approaches to assess and compare the system's tracking behavior.

In the simulation, the parameters of the spacecraft are the nominal inertia and coupling matrices are given [29] by the following:

$$\mathbf{J} = \begin{bmatrix} 973.4 & 0 & 0 \\ 0 & 354.8 & 0 \\ 0 & 0 & 808.5 \end{bmatrix} \mathrm{kg.m}^2,$$

and

$$\mathbf{C} = \begin{bmatrix} 1 & 0.1 & 0.1 \\ 0.5 & 0.1 & 0.01 \\ -1 & 0.3 & 0.01 \end{bmatrix} \mathrm{kg}^{\frac{1}{2}}\mathrm{m}.$$

It's also assumed that three elastic modes exist, such as $\mathbf{A} = \mathrm{diag}(0.602\pi, 1.088\pi, 1.846\pi)\mathrm{rad/s}$ with the damping coefficient $G_1 = G_2 = G_3 = 0.01$.

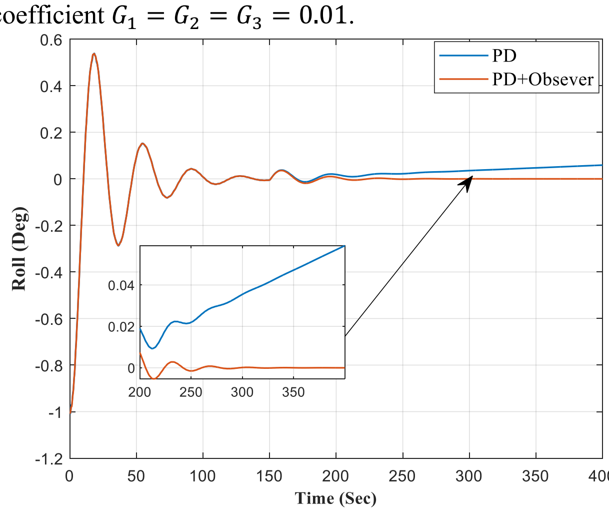

Fig. 2 – Time responses of Roll angle.

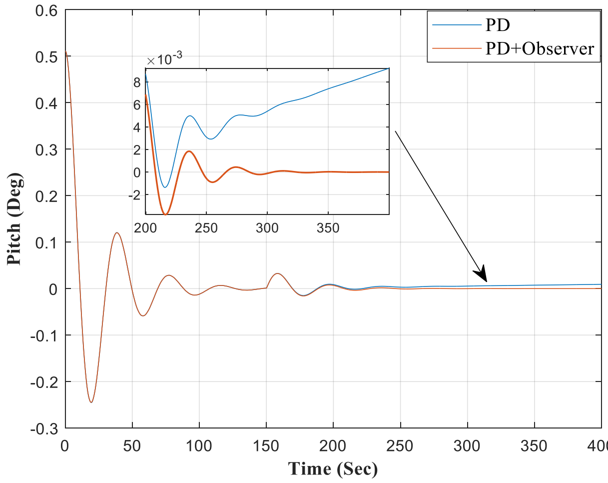

Fig. 3 – Time responses of Pitch angle

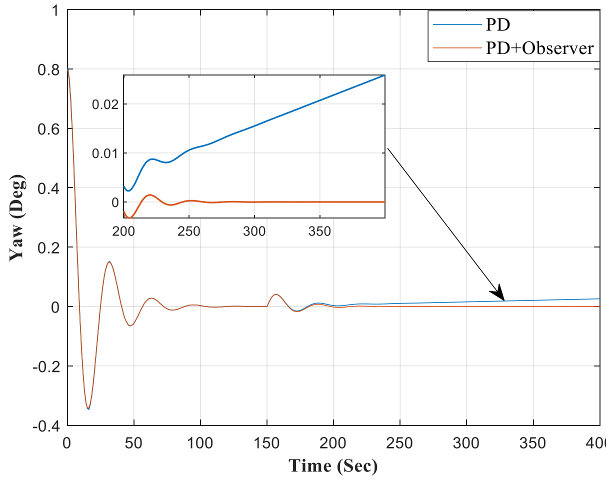

Fig. 4 – Time responses of yaw angle.

The control aims to move the system from the initial to the desired attitude; the simulation results are shown in Fig. 2 to 8.

Under the simulation conducted with the same conditions, Fig. 2, 3, and 4 reveal that all spacecraft attitude angles demonstrate superior dynamic response performance when controlled by the PD with the Observer.

The roll angle tracking error is $< 25 \times 10^{-3}$(deg), the pitch angle tracking error is $< 8 \times 10^{-4}$(deg), and the yaw angle tracking error is $<2\times10^{-3}$(deg). This indicates a significant improvement in pointing accuracy.

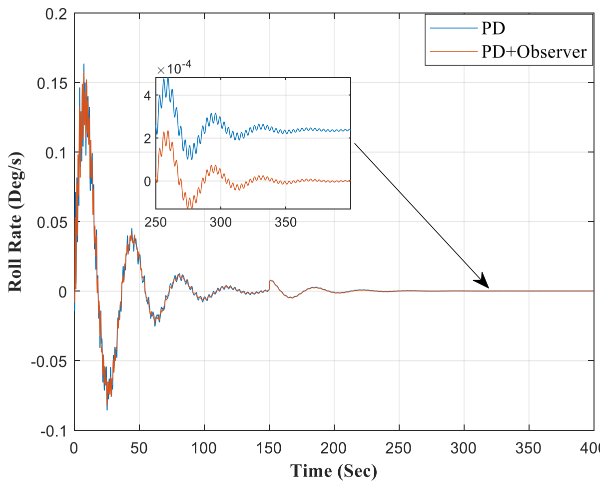

Fig. 5 – Time responses of Roll rate.

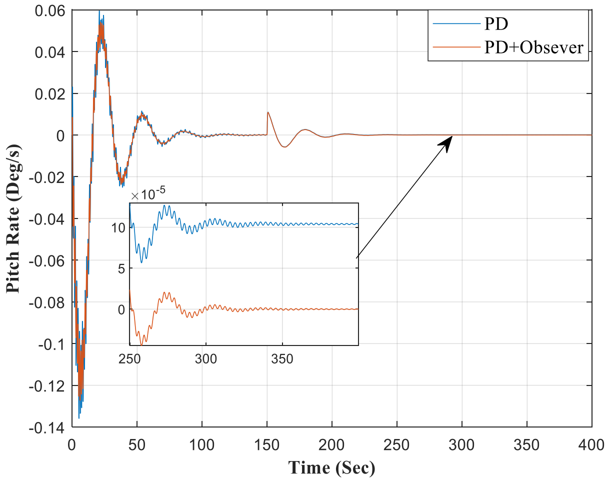

Fig. 6 – Time responses of Pitch rate.

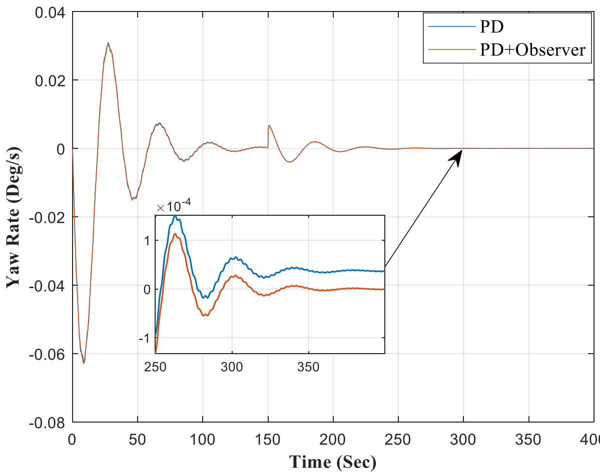

Fig. 7 – Time responses of Yaw rate.

The attitude angular rates, as illustrated in Figs. 5, 6, and 7, indicate an enhancement in system stabilization under the composite controller compared to the achieved using the PD approach alone, particularly in the presence of vibrational disturbances and faults.

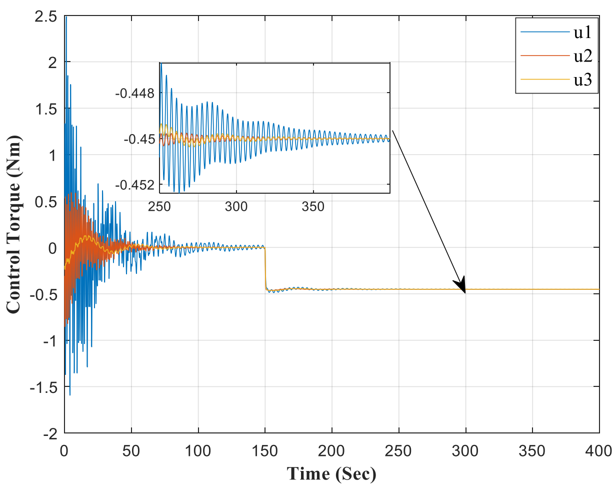

Fig. 8 – Time responses of composite control torque.

As depicted in Fig. 8, the composite control torque is more significant during the initial stages of the simulation. This significance derives from the composite controller, which requires additional energy to estimate and counteract vibrations resulting from faults accurately. Nevertheless, the PD with observer approach demonstrates superior dynamic response performance compared to the PD approach.

For a more comprehensive analysis, the root mean square (RMS) values of error results are computed for 50-100 s, which are presented in the following Table.

Table 1.

RMS error of attitude.

	RMS with Observer	RMS without Observer
Roll angle (°)	0.0015	0.0379
Pitch angle (°)	0.0007	0.0060
Yaw angle (°)	0.0013	0.0166
	Magnitude of error	Magnitude of error
Attitude angle (°)	0.0021	0.0418

5. CONCLUSIONS

This paper uses a novel PD controller and observer scheme to effectively mitigate actuator faults and suppress vibrations in satellite attitude control systems. Our approach enhances steady-state tracking accuracy through a functional observer for fault detection and mitigation and an output feedback-based control system for disturbances compensation. Treating flexible dynamics as disturbances further reinforces the system's performance. The Lyapunov analysis method guarantees the convergence and stability of the closed-loop system. The results reveal the efficiency of our proposed controller, displaying its potential to significantly improve satellite attitude control precision and stability.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Author_1: Conceptualization, methodology, supervision, writing – review and editing.
Author_2: Investigation, formal analysis, visualization, writing the original draft.
Author_3: Software development, validation, resources, writing – review and editing.
Author_4: supervision, writing, and final approval of the manuscript.

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