Research Article

H_∞ Control for Flexible Spacecraft with Time-Varying Input Delay

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This paper is concerned with H_∞ control problem for flexible spacecraft with disturbance and time-varying control input delay. By constructing an augmented Lyapunov functional with slack variables, a new delay-dependent state feedback controller is obtained in terms of linear inequality matrix. These slack variables can make the design more flexible, and the resultant design also can guarantee the asymptotic stability and H_∞ attenuation level of closed-loop system. The effectiveness of the proposed design method is illustrated via a numerical example.

1. Introduction

High-precision attitude control for flexible spacecrafts is a difficult problem in communication, navigation and remote sensing, and so forth. It is because modern spacecrafts often employs large, complex, and lightweight structures such as solar arrays in order to achieve the increased functionality at a reduced launch cost and also provide sustainable energy during space flight [1–4]. Consequently, the complex space structure may lead to the decreased rigidity and low frequency elastic modes. The dynamic model of a flexible spacecraft usually includes the interaction between the rigid and elastic modes [5, 6]. During the control of the rigid body attitude, the unwanted excitation of the flexible modes, together with other external disturbances, measurement, and actuator error, may degrade the performance of attitude control systems (ACSs). Meanwhile, the spacecraft commonly operates in the presence of various disturbances, including gravitational torque, aerodynamic torque, radiation torque, and other environmental and nonenvironmental torques. The problem of disturbance rejection is particularly pronounced in the case of low-earth-orbiting satellites that operate in altitude ranges where their dynamics are substantially affected by most of the disturbances mentioned above [7, 8]. In the face of disturbance and uncertainty, H_∞ methods are ideally

suited for yielding a good performance of flexible spacecrafts. H_∞ control has been used in attitude control systems design in [9, 10] where external disturbance and model uncertainty are considered. An H_∞ multiobjective controller based on the linear matrix inequality (LMI) framework is designed for flexible spacecraft in [11].

On the other hand, in recent years, several studies related to control of flexible spacecraft attitude system with input saturation have been done in [12, 13]. However, the input delay often exists in flexible spacecraft due to the physical structure and energy consumption of the actuators. Although it is not the most important factor to affect the attitude control, it still leads to substantial performance deterioration and even to instability of the system [14, 15]. Hence, stabilization algorithms for such systems that explicitly take input time delay into account are practical interest. Up to now, the issue of control problems for flexible spacecraft subject to both disturbance and input time delay has not been fully investigated and remains to be open and challenging.

In control system design, it is usually desirable to design the control systems which not only is robustly stable but also guarantees an adequate level of performance. One approach to this problem is the so-called guaranteed cost control approach.

Motivated by the preceding discussion, in this paper, we consider H_∞ control problem for flexible spacecraft subject to both disturbance and input time-varying delay. By constructing an augmented Lyapunov functional with slack variables, a new delay-dependent state feedback controller is obtained in terms of linear inequality matrix. These slack variables can make the controller design more flexible and be extended to the systems without time delay. The resultant design also can guarantee the asymptotic stability and H_∞ performances of closed-loop system. Finally, a numerical example is shown to demonstrate the good performance of our method.

Notation. Throughout this paper, R^n denotes the n -dimensional Euclidean space; the space of square-integrable vector functions over $[0, \infty)$ is denoted by $L_2[0, \infty)$; the superscripts “ $\top$ ” and “ -1 ” stand for matrix transposition and matrix inverse, respectively; $P > (\geq 0)$ means that P is a real symmetric and a positive definite (semidefinite). In symmetric block matrices or complex matrix expressions, $\text{diag}\{\cdots\}$ stands for a block-diagonal matrix, and $*$ represents a term that is induced by symmetry. For a vector $v(t)$, its norm is given by $\|v(t)\|_2^2 = \int_0^\infty v^\top(t)v(t)dt$. Matrices, if their dimensions are not explicitly stated, are assumed to be compatible for related algebraic operations.

2. Problem Formulation and Preliminaries

To simplify the problem, only single-axis rotation is considered. We can obtain the single-axis model derived from the nonlinear attitude dynamics of the flexible spacecraft (see also [1, 7]). It is assumed that this model includes one rigid body and one flexible appendage, and the relative elastic spacecraft model is described as follows:

$$\begin{aligned} J\ddot{\theta} + F\ddot{\eta} &= u(t - \tau(t)), \\ \ddot{\eta} + 2\xi\omega\dot{\eta} + \omega^2\eta + F^\top\ddot{\theta} &= 0, \end{aligned} \quad (1)$$

where θ is the attitude angle, J is the moment of inertia of the spacecraft, F is the rigid-elastic coupling matrix, $u(t - \tau(t))$ is the control torque generated by the reaction wheels that are installed in the flexible spacecraft, where $\tau(t)$ satisfies $0 \leq \tau(t) \leq \tau$ and $\dot{\tau}(t) \leq \mu \leq 1$, η is the flexible modal coordinate, ξ is the damping ratio, and ω is the modal frequency. Since the vibration energy is concentrated in low frequency modes in a flexible structure, its reduced order model can be obtained by modal truncation. In this paper, only the first two bending modes are taken into account. Then, we can get

$$(J - FF^\top)\ddot{\theta} = F(2\xi\omega\dot{\eta} + \omega^2\eta) + u(t - \tau(t)). \quad (2)$$

We consider that $F(2\xi\omega\dot{\eta} + \omega^2\eta)$ as the disturbance due to the elastic vibration of the flexible appendages. Denote $x(t) = [\theta(t) \ \dot{\theta}(t)]^\top$, then (2) can be transformed into the state-space form

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t - \tau(t)) + Bd(t), \\ z(t) &= Cx(t), \end{aligned} \quad (3)$$

where

$$\begin{aligned} A &= \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ (J - FF^\top)^{-1} \end{bmatrix}, \\ C &= [I \ 0]. \end{aligned} \quad (4)$$

$d(t) = F(2\xi\omega\dot{\eta} + \omega^2\eta)$ is the disturbance from the flexible appendages and belongs to $L_2[0, \infty)$ and $\|d(t)\| \leq \delta_d$. For system (3), the following control law is employed to deal with the problem of H_∞ control via state feedback

$$u(t) = Kx(t). \quad (5)$$

Then, with the control law (5), the system (3) can be expressed as follows:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + BKx(t - \tau(t)) + Bd(t), \\ z(t) &= Cx(t). \end{aligned} \quad (6)$$

Before stating our main results, the following lemmas are first presented, which will be used in the proof of our result.

Lemma 1 (see [16]). *For any matrix $M > 0$, scalars $b > a$ and $c < d \leq 0$, if there exists a Lebesgue vector function $\omega(s)$, then the following inequalities hold:*

$$\begin{aligned} -\int_a^b \omega^\top(s) M \omega(s) ds &\leq -\frac{1}{b-a} \bar{\omega}^\top(s) M \bar{\omega}(s), \\ -\int_c^d \int_{t+\theta}^t \omega^\top(s) M \omega(s) ds d\theta &\leq -\frac{2}{c^2 - d^2} \bar{\omega}^\top(s) M \bar{\omega}(s), \end{aligned} \quad (7)$$

where $\bar{\omega}(s) = \int_a^b \omega^\top(s) ds$, $\bar{\omega}(s) = \int_c^d \int_{t+\theta}^t \omega(s) ds d\theta$.

3. Main Result

First of all, a new version of delay-dependent bounded real lemma for the system (6) is proposed in this section.

Theorem 2. *Given scalars $\gamma > 0$, $\mu \leq 1$. For any delay $\tau(t)$ satisfying $0 \leq \tau(t) \leq \tau$, the system (6) is asymptotically stable and satisfies $\|z(t)\|_2 < \gamma \|d(t)\|_2$ for any nonzero $d(t) \in L_2[0, \infty)$ under the zero initial condition if there exist matrices $P_1 > 0$, $Q_1 > 0$, $Q_2 > 0$, $R_1 > 0$, $R_2 > 0$, P_2 , and P_3 such that the following inequality holds:*

$$\begin{bmatrix} \Omega + \bar{\Omega} & Y \\ Y^\top & -\gamma^2 I \end{bmatrix} < 0, \quad (8)$$

where

$$\Omega = \begin{bmatrix} \Omega_{11} & \Omega_{12} & \Omega_{13} & 0 & \frac{1}{\tau}R_2 \\ * & \Omega_{22} & P_3^\top BK & 0 & 0 \\ * & * & \Omega_{33} & \frac{1}{\tau}R_1 & 0 \\ * & * & * & -Q_1 - \frac{1}{\tau}R_1 & 0 \\ * & * & * & * & -\frac{2}{\tau^2}R_2 \end{bmatrix},$$

$$Y = \begin{bmatrix} P_2^\top B \\ P_3^\top B \\ 0 \\ 0 \\ 0 \end{bmatrix},$$

$$\bar{\Omega} = \text{diag}\{C^\top C, 0, 0, 0, 0\},$$

$$\Omega_{11} = P_2^\top A + A^\top P_2 + Q_1 + Q_2 - \frac{1}{\tau}R_1 - 2R_2,$$

$$\Omega_{12} = P_1 - P_2^\top + A^\top P_3,$$

$$\Omega_{13} = P_2^\top BK + \frac{1}{\tau}R_1,$$

$$\Omega_{22} = -P_3 - P_3^\top + \tau R_1 + \frac{\tau^2}{2}R_2,$$

$$\Omega_{33} = -(1 - \mu)Q_2 - \frac{2}{\tau}R_1.$$

Proof. The first step is to analyze the asymptotic stability of the system (6). Consider the system (6) in the absence of $d(t)$, that is,

$$\dot{x}(t) = Ax(t) + BKx(t - \tau(t)). \quad (10)$$

Choose the following Lyapunov-Krasovskii functional:

$$\begin{aligned} V(t) = & \xi^\top(t) EP\xi(t) + \int_{t-\tau}^t x^\top(s) Q_1 x(s) ds \\ & + \int_{t-\tau(t)}^t x^\top(s) Q_2 x(s) ds \\ & + \int_{-\tau}^0 \int_{t+\theta}^t \dot{x}^\top(s) R_1 \dot{x}(s) ds d\theta \\ & + \int_{-\tau}^0 \int_{\theta}^0 \int_{t+\nu}^t \dot{x}^\top(s) R_2 \dot{x}(s) ds d\theta d\nu, \end{aligned} \quad (11)$$

where

$$E = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}, \quad P = \begin{bmatrix} P_1 & 0 \\ P_2 & P_3 \end{bmatrix}, \quad \xi(t) = \begin{bmatrix} x(t) \\ \dot{x}(t) \end{bmatrix}, \quad (12)$$

$$P_1 > 0, \quad Q_i > 0, \quad R_i > 0, \quad i = 1, 2.$$

Then, along the solution of the system in (10), the time derivative of $V(t)$ is given by

$$\begin{aligned} \dot{V}(t) = & 2\xi^\top(t) P^\top \begin{bmatrix} \dot{x}(t) \\ -\dot{x}(t) + Ax(t) + BKx(t - \tau(t)) \end{bmatrix} \\ & + x^\top(t) (Q_1 + Q_2) x(t) \\ & - x^\top(t - \tau) Q_1 x(t - \tau) \\ & - (1 - \mu) x^\top(t - \tau(t)) Q_2 x(t - \tau(t)) \\ & + \dot{x}^\top(t) \left(\tau R_1 + \frac{\tau^2}{2} R_2 \right) \dot{x}(t) \\ & - \int_{t-\tau}^t \dot{x}^\top(s) R_1 \dot{x}(s) ds - \int_{-\tau}^0 \int_{t+\theta}^t \dot{x}^\top(s) R_2 \dot{x}(s) ds d\theta. \end{aligned} \quad (13)$$

From Lemma 1, It is easily shown that

$$\begin{aligned} & - \int_{t-\tau}^t \dot{x}^\top(s) R_1 \dot{x}(s) ds \\ & = - \int_{t-\tau}^{t-d(t)} \dot{x}^\top(s) R_1 \dot{x}(s) ds \\ & \quad - \int_{t-d(t)}^t \dot{x}^\top(s) R_1 \dot{x}(s) ds \\ & \leq [x^\top(t) \quad x^\top(t - d(t)) \quad x^\top(t - \tau)] \\ & \quad \times \begin{bmatrix} -\frac{R_1}{\tau} & \frac{R_1}{\tau} & 0 \\ * & -\frac{\tau R_1}{\tau} & \frac{R_1}{\tau} \\ * & * & -\frac{\tau R_1}{\tau} \end{bmatrix} \begin{bmatrix} x(t) \\ x(t - d(t)) \\ x(t - \tau) \end{bmatrix}. \end{aligned} \quad (14)$$

Similarly, the following inequality is also true:

$$\begin{aligned} & - \int_{-\tau}^0 \int_{t+\theta}^t \dot{x}^\top(s) R_2 \dot{x}(s) ds d\theta \\ & \leq -\frac{2}{h^2} \left(\int_{-\tau}^0 \int_{t+\theta}^t \dot{x}(s) ds d\theta \right)^\top R_2 \\ & \quad \times \left(\int_{-\tau}^0 \int_{t+\theta}^t \dot{x}(s) ds d\theta \right) \\ & = \begin{bmatrix} x^\top(t) & \int_{t-\tau}^t x^\top(s) ds \end{bmatrix} \begin{bmatrix} -2R_2 & \frac{2}{\tau}R_2 \\ * & -\frac{\tau}{\tau^2}R_2 \end{bmatrix} \\ & \quad \times \begin{bmatrix} x(t) \\ \int_{t-\tau}^t x(s) ds \end{bmatrix}. \end{aligned} \quad (15)$$

Substituting (14) and (15) into (13) gives

$$\dot{V}(t) \leq \eta^\top(t) \Omega \eta(t), \quad (16)$$

where $\eta(t) = [x(t) \ \dot{x}(t) \ x(t - \tau(t)) \ x(t - \tau) \ \int_{t-\tau}^t x(s)ds]^\top$ and Ω is defined in (8). Applying the Schur complement to (8) gives $\Omega < 0$, which implies $\dot{V}(t) < 0$. Hence, the system (6) is asymptotically stable. Next, we will establish the H_∞ performance of the uncertain delay system (6) under zero initial condition. Let

$$J(t) = \int_0^t [z^\top(s) z(s) - \gamma^2 d^\top(s) d(s)] ds. \quad (17)$$

It can be shown that for any nonzero $d(t) \in L_2[0, \infty)$ and $t > 0$,

$$J(t) \leq \int_0^t [z^\top(s) z(s) - \gamma^2 d^\top(s) d(s) + \dot{V}(s)] ds. \quad (18)$$

It is noted that

$$\begin{aligned} & z^\top(s) z(s) - \gamma^2 d^\top(s) d(s) \\ &= \phi^\top(t) \text{diag}\{C^\top C, 0, 0, 0, 0, -\gamma^2 I\} \phi(t), \end{aligned} \quad (19)$$

where $\phi(t) = [\eta(t), d(t)]$ and the time derivative of $\dot{V}(x_s)$ along the solution of (6) gives

$$\dot{V}(s) \leq \phi^\top(t) \begin{bmatrix} \Omega & Y \\ Y^\top & 0 \end{bmatrix} \phi(t). \quad (20)$$

Hence, $J(t) < 0$ follows from (8), (19) and (20), which implies that $\|z(t)\|_2 < \gamma \|d(t)\|_2$ holds for any nonzero $d(t) \in L_2[0, \infty)$. $\square$

From the proof procedure of Theorem 2, one can see that a new Lyapunov-Krasovskii functional is constructed by employing slack variables P_2 and P_3 . It is worth pointing out that the matrices P_2 and P_3 are useless for reducing the conservatism of stability conditions by using the equivalence idea in [17, 18]. However, they separates the Lyapunov function matrix $P_1 > 0$ from system matrices A and B , that is, there are no terms containing the product of P_1 and any of them, which is useful for the design of H_∞ controller later on.

On the basis of Theorem 2, we will present a design method of H_∞ stabilizing controllers in the following.

Theorem 3. Given scalars $\gamma > 0$, $\mu \leq 1$ and $\varepsilon \neq 0$. For any delay $\tau(t)$ satisfying $0 \leq \tau(t) \leq \tau$, the system (6) is asymptotically stable and satisfies $\|z(t)\|_2 < \gamma \|d(t)\|_2$ for any nonzero $d(t) \in L_2[0, \infty)$ under the zero initial condition if there exist matrices $\bar{P}_1 > 0$, $\bar{Q}_1 > 0$, $\bar{Q}_2 > 0$, $\bar{R}_1 > 0$, $\bar{R}_2 > 0$, F , and invertible matrix $\bar{P}_2$ such that the following inequality holds:

$$\begin{bmatrix} \Pi & \bar{Y} \\ \bar{Y}^\top & -\gamma^2 I \end{bmatrix} < 0, \quad (21)$$

where

$$\begin{aligned} \Pi = & \begin{bmatrix} \Pi_{11} & \Pi_{12} & \Pi_{13} & 0 & \frac{1}{\tau} \bar{R}_2 & \bar{P}_2^\top C^\top \\ * & \Pi_{22} & \varepsilon BF & 0 & 0 & 0 \\ * & * & \Pi_{33} & \frac{1}{\tau} \bar{R}_1 & 0 & 0 \\ * & * & * & -\bar{Q}_1 - \frac{1}{\tau} \bar{R}_1 & 0 & 0 \\ * & * & * & * & -\frac{2}{\tau^2} \bar{R}_2 & 0 \\ * & * & * & * & * & -I \end{bmatrix}, \\ \bar{Y} = & \begin{bmatrix} B \\ \varepsilon B \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \end{aligned} \quad (22)$$

$$\Pi_{11} = A \bar{P}_2 + \bar{P}_2^\top A^\top + \bar{Q}_1 + \bar{Q}_2 - \frac{1}{\tau} \bar{R}_1 - 2 \bar{R}_2,$$

$$\Pi_{12} = \bar{P}_1 - \bar{P}_2 + \varepsilon \bar{P}_2^\top A^\top,$$

$$\Pi_{13} = BF + \frac{1}{\tau} \bar{R}_1,$$

$$\Pi_{22} = -\varepsilon \bar{P}_2 - \varepsilon \bar{P}_2^\top + \tau \bar{R}_1 + \frac{\tau^2}{2} \bar{R}_2,$$

$$\Pi_{33} = -(1 - \mu) \bar{Q}_2 - \frac{2}{\tau} \bar{R}_1.$$

Moreover, the feedback gain matrices K are given by

$$K = F \bar{P}_2^{-1}. \quad (23)$$

Proof. Define some matrices as follows:

$$\begin{aligned} P_2 &= \bar{P}_2^{-1}, & P_3 &= \frac{1}{\varepsilon} \bar{P}_2^{-1}, & P_1 &= P_2^\top \bar{P}_1 P_2, \\ Q_1 &= P_2^\top \bar{Q}_1 P_2, & Q_2 &= P_2^\top \bar{Q}_2 P_2, \\ R_1 &= P_2^\top \bar{R}_1 P_2, & R_2 &= P_2^\top \bar{R}_2 P_2. \end{aligned} \quad (24)$$

Then, premultiplying (21) by $\text{diag}\{P_2^\top, P_2^\top, P_2^\top, P_2^\top, P_2^\top, I, I\}$ and postmultiplying by $\text{diag}\{P_2, P_2, P_2, P_2, P_2, I, I\}$, we can get the following inequality:

$$\begin{bmatrix} \Omega & W & Y \\ W^\top & -I & 0 \\ Y^\top & 0 & -\gamma^2 I \end{bmatrix} < 0, \quad (25)$$

where $W^\top = [C \ 0 \ 0 \ 0 \ 0]$. Using Schur complement, from (25), it is clear that (8) holds. As a result, the closed-loop system (6) is asymptotically stable and satisfies $\|z(t)\|_2 < \gamma \|d(t)\|_2$. The proof is thus completed. $\square$

Comparing with the traditional controller design method, the matrix $\bar{P}_2$ is invertible matrix instead of positive definite matrix, which make the design more flexible. Moreover, this method also can be extended to the systems without time delay.

FIGURE 1: Spacecraft with flexible appendages.

FIGURE 2: The responses of pitch attitude θ .

4. Numerical Examples

In this section, we consider flexible spacecraft including one rigid body and one flexible appendage depicted in Figure 1. Numerical application of the proposed control schemes to the attitude control of such system is presented using MATLAB/SIMULINK software. In this paper, we only consider the attitude in the pitch channel. Four bending modes are considered for the practical spacecraft model at $\omega_1 = 3.17$ rad/s and $\omega_2 = 7.18$ rad/s with damping $\xi = 0.001$ and $\xi = 0.0015$. We suppose that $F = [F_1 \ F_2]$, where the coupling coefficients of the first two bending modes are $F_1 = 1.27814$, $F_2 = 0.91756$, and $J = 35.72$ kgm² which is the nominal principal moment of inertia of pitch axis. The flexible spacecraft is supposed to move in a circular orbit with the altitude of 500 km, then the orbit rate $n = 0.0011$ rad/s. The initial pitch attitude be of the spacecraft are $\theta(0) = 0.08$ rad and $\dot{\theta}(0) = 0.001$ rad/s. And H_∞ performance index is supposed to $\gamma = 0.1$, and time delay satisfies $\tau = 0.3$ and $u = 0.1$. The tuning parameter is chosen as $\varepsilon = 1$. The response of pitch attitude θ , $\dot{\theta}$, and the control are shown in Figures 2, 3, and 4, respectively. From these figures, we can see that our proposed method has a good performance under disturbance and input time delay.

FIGURE 3: The responses of pitch attitude $\dot{\theta}$. FIGURE 4: The responses of control $u(t - \tau(t))$.

5. Conclusion

In this paper, H_∞ control problem for flexible spacecraft with disturbance and input time-varying delay has been investigated. The LMI-based condition has been formulated for the existence of the admissible controller, which ensures that the closed-loop system is asymptotically stable with a H_∞ disturbance attenuation level. Further improvement in precision attitude control for flexible spacecrafts will be considered in our future work.

Conflict of Interests

The authors of this paper do not have a direct financial relation with the commercial identity mentioned in this paper. This does not lead to a conflict of interests to any of the authors.

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