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Attitude stabilization of a flexible spacecraft under actuator complete failure ☆

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ABSTRACT

This paper considers the attitude and angular velocity stabilization problem of a class of flexible spacecraft under actuator complete failure. Firstly a new model simplification strategy is put forward to weaken the coupling effects. Then an adaptive observer-based estimation method is proposed to estimate the uncertainty of flexibility, based on which a feedback fault-tolerant control scheme is further developed which guarantees the system stability and asymptotic attitude converging properties. The simulation results illustrate the efficiency of the theoretical results.

1. Introduction

The free-flying spacecraft with the capabilities of accurate attitude maneuver, tracking and pointing is required to accomplish advanced space missions, such as earth observation and space monitoring. To solve such an attitude problem, an effective control scheme is needed to ensure the desired system stability and attitude stable properties, especially in the presence of unknown flexible appendages and actuator faults even complete failure. In the presence of complete failure of actuators, the spacecraft becomes under-actuated.

Various control laws have been proposed for under-actuated rigid spacecraft, see survey paper [1] and the references therein and the papers [30–37]. The design methods often rely on a set of rigorous conditions on spacecraft dynamics. The problem of attitude stabilization using less than three control torques started with the work of Crouch [2], Byrnes and Isidori [3], and later by Krishnan [4], Tsiotras [5], Morin and Samson [6]. The work by Krishnan [4] and later by Tsiotras [5] dealt with the global stabilization of an axisymmetric spacecraft for the special case when the initial spin-rate is $\omega_3(0) = 0$ using time-invariant feedback control laws. On the other hand, the work by Morin and Samson [6] dealt with the local stabilization of a general rigid spacecraft using time-varying controllers. Time-varying controllers are used in order to circumvent the topological obstruction to smooth stabilizability due to the Brockett's condition [7]. Typically, non-smooth, continuous controllers must be used to achieve exponential convergence rates and avoid oscillations.

On the other hand, several fault-tolerant control methods have been developed to compensate for the actuator faults in current literatures for flexible spacecraft, e.g. [8–15], to name a few. The dynamics of flexible spacecraft attitude system are highly nonlinear and have strong coupling between flexible and rigid bodies. People pay more attention to the flexible spacecraft stabilization problem. As for the application of fault-tolerant control to flexible spacecraft, Xiao and Hu dealt with fault-tolerant attitude tracking control for flexible spacecraft with loss of actuator effectiveness in [16,17]. In [18] and [19], Yang dealt with attitude control problems for a spacecraft with intermittent controller faults by a stochastic switched system and by a state-varying switched system respectively, and the attitude control performance can be maintained. In [20], Ma and Jiang dealt with a fault-tolerant adaptive control scheme for attitude tracking of flexible spacecraft with unknown inertia parameters, external disturbance, and actuator faults which guaranteed the system stability and asymptotic attitude tracking properties. In [21], Jiang designed a sliding mode controller for the flexible spacecraft with multiplicative and additive faults and the input-to-state stability of the system was ensured. In [36], Du and Li investigated the finite-time attitude stabilization problem for a rigid spacecraft using homogeneous method with actuator saturation.

However, to the best of our knowledge, until now no result has been reported on the attitude control problem of flexible spacecraft

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with actuator complete failure. Moreover, the attitude control and vibration suppression of flexible under-actuated spacecraft are still open problems [22]. In this paper, an adaptive observer-based fault-tolerant control scheme is designed for the attitude system of flexible spacecraft with actuator failure. In contrast with the existing literatures on attitude control for under-actuated rigid spacecraft and actuator fault compensation for flexible spacecraft, the main contributions of this paper are in three aspects:

(1) Since the dynamics of flexible spacecraft attitude system are highly nonlinear, and there are strong couplings between flexible and rigid bodies, a new model simplification method based on homogeneous system approach is developed for attitude system of spacecraft, which can weaken the coupling effects between the angular velocity and the flexible vibration, and between the angular velocity and the attitude.
(2) A new adaptive observer is developed to estimate the time-varying uncertainty of flexibility. The norm bound of the error between estimated value and true value is determined which can be rendered arbitrarily small.
(3) A novel control scheme using attitude and angular velocity feedback is developed to compensate for the uncertainties of flexibility and actuator faults. The proposed control algorithm can ensure the system stability such that the attitude and the angular velocity converge to a bounded region.

The remaining of this paper is organized as follows: in Section 2, details of the dynamics and kinematics of flexible spacecraft under actuator complete failure are presented. In Section 3, a new simplification method for attitude system using the properties of homogeneity is put forward. In Section 4, a feedback fault-tolerant control scheme is designed to provide the system stability. Section 5 provides simulation results, followed by conclusions in Section 6.

2. Problem formulation

In this section, the dynamics and attitude kinematics of under-actuated flexible spacecraft are introduced first, and then the control objective is formulated.

2.1. Dynamics for flexible spacecraft

The rotational motion of flexible spacecraft can be described by Euler's equations of motion. With the assumption that the rigid body has a body-fixed reference frame along its principal axes of inertia with the origin at the center of mass. The dynamic equations of a spacecraft with flexible appendages, actuated by reaction wheels can be described by [8,38]

$$J\dot{\omega} + \delta^T\ddot{\eta} = -\omega^\times\left(J\omega + \delta^T\dot{\eta}\right) + T \tag{1}$$

$$\ddot{\eta} + C\dot{\eta} + K\eta = -\delta\dot{\omega} \tag{2}$$

where $\omega = [\omega_1, \omega_2, \omega_3]^T \in \Omega \subset \Re^3$ is the angular velocity of the main body, $J = J^T \in \Re^{3\times3}$ is the total symmetric inertia matrix of the spacecraft. $T = [T_1, T_2, T_3]^T$ is the control torque generated by reaction wheels. Notation $m^\times$ with respect to $m = [m_1, m_2, m_3]^T$ denotes a skew-symmetric matrix which can be expressed as

$$m^\times \triangleq \begin{bmatrix} 0 & -m_3 & m_2 \\ m_3 & 0 & -m_1 \\ -m_2 & m_1 & 0 \end{bmatrix} \tag{3}$$

In (2), $\eta \in \Re^N$ is the model coordinate vector relative to the main body and N is the dimension of flexible modes. $\delta \in \Re^{N\times3}$ denotes the coupling matrix between flexible and rigid dynamics whose column vectors are orthogonal, $C = diag(2\xi_1\Lambda_1, 2\xi_2\Lambda_2, \ldots, 2\xi_N\Lambda_N)$ and $K = diag(\Lambda_1^2, \Lambda_2^2, \ldots, \Lambda_N^2)$ are respectively the damping and stiffness matrices with the natural frequencies Λ_i and the associated damping ξ_i.

Substituting (2) into (1) yields

$$J_0\dot{\omega} + \omega^\times J\omega = -\omega^\times\delta^T\dot{\eta} + \delta^T C\dot{\eta} + \delta^T K\eta + T \tag{4}$$

where $J_0 = J - \delta^T\delta$ denotes the main inertia matrix which is diagonal and nonsingular. Then the dynamic Eq. (1) can be rewritten as

$$\dot{\omega}_1 = \frac{J_2 - J_3}{J_{01}}\omega_2\omega_3 + \frac{T_1}{J_{01}} + f_1(\eta, \dot{\eta}) + g_1(\omega, \dot{\eta}) \tag{5}$$

$$\dot{\omega}_2 = \frac{J_3 - J_1}{J_{02}}\omega_3\omega_1 + \frac{T_2}{J_{02}} + f_2(\eta, \dot{\eta}) + g_2(\omega, \dot{\eta}) \tag{6}$$

$$\dot{\omega}_3 = \frac{J_1 - J_2}{J_{03}}\omega_1\omega_2 + \frac{T_3}{J_{03}} + f_3(\eta, \dot{\eta}) + g_3(\omega, \dot{\eta}) \tag{7}$$

where

$$f(\cdot) = \begin{pmatrix} f_1(\cdot) \\ f_2(\cdot) \\ f_3(\cdot) \end{pmatrix} = J_0^{-1}(\delta^T C\dot{\eta} + \delta^T K\eta), \qquad \begin{pmatrix} g_1(\cdot) \\ g_2(\cdot) \\ g_3(\cdot) \end{pmatrix} = -J_0^{-1}\omega^\times\delta^T\dot{\eta}$$

For the sake of simplicity, define

$$a \triangleq \frac{J_2 - J_3}{J_{01}}, \quad c \triangleq \frac{J_3 - J_1}{J_{02}}, \quad \varepsilon \triangleq \frac{J_1 - J_2}{J_{03}} \neq 0$$

Remark 1. The spacecraft under consideration in this paper is a flexible body which is almost axisymmetric about the under-actuated axis. A small parameter ε gives a measure of the non-symmetry of the spacecraft [29]. When $\varepsilon = 0$, the flexible body is axisymmetric. But a real spacecraft can never be completely axisymmetric, implying that even if ε is very small there will be a slow rotation about the symmetric axis.

Clearly, the system (5)–(7) is under-actuated if one of the terms of T_i/J_{0i} $(i = 1, 2, 3)$ is equal to zero. Without loss of generality, the case $T_3 = 0$ is considered. Define the control torques $u_1 \triangleq T_1/J_{01}$ and $u_2 \triangleq T_2/J_{02}$. Substituting the above expressions into Eqs. (5)–(7) leads to the following dynamic equations

$$\dot{\omega}_1 = a\omega_2\omega_3 + u_1 + f_1(\eta, \dot{\eta}) + g_1(\omega, \dot{\eta}) \tag{8}$$

$$\dot{\omega}_2 = c\omega_3\omega_1 + u_2 + f_2(\eta, \dot{\eta}) + g_2(\omega, \dot{\eta}) \tag{9}$$

$$\dot{\omega}_3 = \varepsilon\omega_1\omega_2 + f_3(\eta, \dot{\eta}) + g_3(\omega, \dot{\eta}) \tag{10}$$

No matter which axis is the under-actuated axis, the dynamic model can be described as the same as the form of (8)–(10). Thus the fault-tolerant control scheme put forward in this paper is also suitable for the case of $T_1 = 0$ or $T_2 = 0$.

Assumption 1. *The vibration of flexible appendages η and its derivative $\dot{\eta}$ are bounded, there exist some positive constants f^1 and f^0 such that $\|f(\cdot)\| \le f^1$, and $\|\dot{f}(\cdot)\| \le f^0$.*

Remark 2. Note that flexible appendages of spacecraft are constructed by advanced materials and damping is certain. Both the