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Disturbance observer based attitude control for flexible spacecraft with input magnitude and rate constraints

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ABSTRACT

In this paper, we investigate the problem of attitude control design for flexible spacecraft with external disturbance, input magnitude and rate constraints. First, a disturbance observer is designed to estimate and compensate for the disturbances including the external disturbance and vibration from the flexible appendages. Then, based on the disturbance observer, a sample state feedback control scheme is proposed for flexible spacecraft subject to input magnitude and rate constrains, using the linear matrix inequality (LMI) and Lyapunov direct method. Finally, the results are illustrated using numerical simulations for control performance verification.

1. Introduction

Spacecrafts have gained much attention in the past decades for the purpose of remote sensing, communication and so on. Considering a complex environment and space mission constraints, flexible spacecraft characterized by light weight structure, limitation of mass, low energy consumption and reduced launch cost, are widely used. Such flexible spacecrafts have a central rigid hub and long flexible appendages such as solar panels. However, due to the flexible property of flexible appendages, the unwanted deflection of the flexible modes and other external disturbances have a significant influence on the dynamics and control performance of the flexible spacecraft. Therefore, high-precision attitude control for flexible spacecrafts is a difficult problem and an important research topic.

Recently, a number of methods have been developed for the attitude control of flexible spacecrafts, including variable structure control [1,2], positive position feedback control [3], adaptive control [4,5], fault-tolerant control [6,7], disturbance observer based control [8,9], Disturbance Compensator based control [10], $H\infty$ control [11,12] and some discrete control methods [13,14]. In [1], a discontinuous attitude control law in the form of the input voltage of the reaction wheel is derived to control the orientation of the spacecraft based on the sliding mode control (SMC) theory. SMC is an efficient and simple control scheme to deal with disturbances and model uncertainty, but the chattering phenomenon caused by SMC has restricted its practical application. In [12], based on the $H\infty$ and LMI technology, a general approach for controller design for systems with large flexible appendages is presented. A fault-tolerant attitude stabilization control scheme is proposed in [6] for flexible spacecraft with the angular velocity magnitude eliminated.

Many practical dynamic systems have the input saturation due to the limitation of the actuators or the inherent physical constraints of the systems. The saturation often degrades the performance of the control system or leads to the instability if they are ignored in the control design. Therefore, the problem for the saturation constraints is a topic of great importance, and many methods to solve this problem are proposed [15–20]. In [21,18], boundary control schemes are proposed for flexible manipulator with input saturation, where smooth hyperbolic functions are used to handle input saturation. In [22], adaptive impedance control is developed for an n-link robotic manipulator with input saturation, and the input saturation is handled by designing an auxiliary system. Another approach is to design an anti-windup compensator to weaken the influence of saturation. In [23], a general formulation of the problem of multi-variable anti-windup bumpless transfer (AWBT) controller synthesis is presented, where the AWBT controller synthesis, using static compensation, is cast as a convex optimization over linear matrix inequalities. In [4], a control scheme is proposed for rotational manoeuvre and vibration stabilization of a flexible spacecraft in the presence of input saturation. The papers about input saturation problems mentioned above consider only magnitude input constraints.

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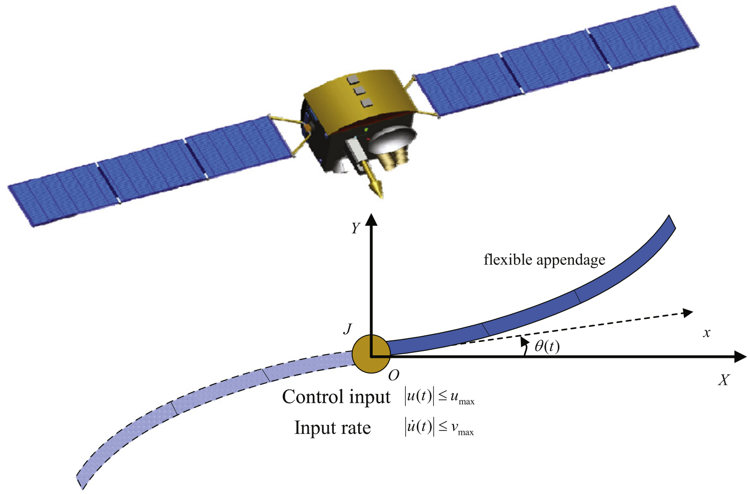

Fig. 1. Diagram of a flexible spacecraft.

Considering the safe use of actuator, the input rate should be taken into account [24,25]. In [26], a feedback control law is designed to track attitude for a rigid body subject to torque-magnitude and rate-saturation limits. In [27], an algorithm based on the iterative solution of linear matrix inequalities-based problems is proposed to compute the control law which is designed for stabilization of linear systems subject to control amplitude and rate saturation. An anti-windup scheme is presented for an aircraft with actuator magnitude and rate saturation. Disturbances and model uncertainty are not taken into accountant in these literatures. In [28], smooth hyperbolic tangent function is used to design robust attitude tracking control of spacecraft under control input magnitude and rate saturations. However, this design process is complex and the convergence error may be large.

In this paper, we consider the problem of attitude maneuver control for a flexible spacecraft with external disturbances, input magnitude and rate constraints. The main challenge of such a problem arises from three aspects including effect of vibration from flexible appendages, external disturbances, and the pre-set constraint boundary of the input magnitude and rate. Therefore, we first design a disturbance observer to estimate and compensate for the effect of the disturbance including external disturbance and vibrations. Using the disturbance observer, a sample LMI-based state feedback control scheme is proposed for flexible spacecraft with input magnitude and rate constrains.

The rest of the paper is organized as follows. The problem formulation is given in Section 2. Section 3 presents the DOBC scheme design. Numerical simulations are demonstrated in Section 4 to show the effectiveness of the proposed control law. A conclusion is presented in Section 5.

Notation: Throughout this paper, $\mathbf{R}$, $\mathbf{R}^n$, and $\mathbf{R}^{m\times n}$ denote the set of all real numbers, n-dimensional Euclidean space, and the set of all $m \times n$ matrices, respectively. Identity matrix, of appropriate dimension, will be denoted by I. For a symmetric matrix P, $P > 0$ $(< 0, \le 0)$ means that is real symmetric positive definite (negative definite, negative semi-definite, respectively). The superscript T is used for the transpose of a vector or a matrix. The symbol $*$ is adopted to avoid repetition in formulas involving matrices, as per the following expression:

$$\begin{bmatrix} X+[Y+Z+*] & M \\ * & N \end{bmatrix} \triangleq \begin{bmatrix} X+[Y+Z+Y^T+Z^T] & M \\ M^T & N \end{bmatrix}$$

2. Problem statement

2.1. Dynamic analysis

In this paper, we consider a flexible spacecraft that can undergo a single axis rotation. Assume that the flexible spacecraft is composed of one rigid body and only one uniform flexible appendage, as shown in Fig. 1. XOY and xoy represent the global inertial coordinate system and the body-fixed coordinate system attached to the appendage, respectively. The flexible spacecraft model is described as follows [29,30]

$$J\ddot{\theta}(t) + F^T\ddot{q}(t) = u(t) + d_0(t) \quad (1)$$

$$\ddot{q}(t) + T\dot{q}(t) + Cq(t) + F\ddot{\theta}(t) = 0 \quad (2)$$

where $\theta(t) \in \mathbf{R}$ is the rotation angle of the body fixed frame with respect to the reference frame XOY, $J \in \mathbf{R}$ the moment of inertia of the spacecraft, $u(t) \in \mathbf{R}$ the control torque, and $d_0(t) \in \mathbf{R}$ represents the merged disturbance torque including space environmental torques and unmodeled uncertainties, $q(t) \in \mathbf{R}^n$ the modal coordinate vector, $F \in \mathbf{R}^n$ the rigid-elastic coupling matrix, $T = diag\{2\xi_1\omega_1, \cdots, 2\xi_n\omega_n\} \in \mathbf{R}^{n\times n}$ the damping matrices, $C = diag\{\omega_1^2, \cdots, \omega_n^2\} \in \mathbf{R}^{n\times n}$ the damping matrices, n the number of elastic modes considered, ξ_i $(i = 1, \cdots, n)$ the corresponding damping, ω_i $(i = 1, \cdots, n)$ the natural frequencies.

The model of flexible spacecraft given by (1) and (2) is infinite dimension, and the high dimension of the model is too complex to derive the control scheme. Since the low-frequency modes are generally dominant in a flexible system, and are major concerns for vibration suppression, its reduced order model can be obtained by modal truncation. In this paper, only the first two modes of vibration and their derivatives are taken into account.

Denote $x(t) = [\theta(t), \dot{\theta}(t)]^T$, then (1) and (2) can be transformed into the following form:

$$\dot{x}(t) = Ax(t) + Bu(t) + Bd(t) \quad (3)$$

where $A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ (J - FF^T)^{-1} \end{bmatrix}$,
$d(t) = d_0(t) + F\,(T\dot{q}(t) + Cq(t))$ is considered as the lumped disturbance from the flexible appendages and $d_0(t)$.

2.2. Preliminaries

This part presents the following necessary assumption and lemma, which will be needed in the subsequent design and analysis of the control scheme and the disturbance observer.