Acta Astronautica 136 (2017) 166–175

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Robust high-precision attitude control for flexible spacecraft with improved mixed H_2/H_∞ control strategy under poles assignment constraint

Chuang Liu, Dong Ye*, Keke Shi, Zhaowei Sun

Research Center of Satellite Technology, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Keywords:
Flexible spacecraft
Attitude stabilization
Active vibration suppression
Improved mixed H_2/H_∞ control
Poles assignment

ABSTRACT

A novel improved mixed H_2/H_∞ control technique combined with poles assignment theory is presented to achieve attitude stabilization and vibration suppression simultaneously for flexible spacecraft in this paper. The flexible spacecraft dynamics system is described and transformed into corresponding state space form. Based on linear matrix inequalities (LMIs) scheme and poles assignment theory, the improved mixed H_2/H_∞ controller does not restrict the equivalence of the two Lyapunov variables involved in H_2 and H_∞ performance, which can reduce conservatives compared with traditional mixed H_2/H_∞ controller. Moreover, it can eliminate the coupling of Lyapunov matrix variables and system matrices by introducing slack variable that provides additional degree of freedom. Several simulations are performed to demonstrate the effectiveness and feasibility of the proposed method in this paper.

1. Introduction

Large flexible spacecraft systems have been developed for future applications in widespread communications, remote sensing and related scientific researches in space [1]. Modern large spacecraft usually employ flexible appendages such as solar arrays and antennas. In rotational maneuvers of such spacecraft, elastic deformations in the flexible appendages often appear. Therefore, it poses a challenging task for spacecraft designers to design the controller so as to provide high pointing precision while effectively suppress the induced vibration. Besides, spacecraft is always subject to environmental or non-environmental disturbances, and the requirement for attitude stabilization performance becomes more rigorous. Using some actuators such as on-off thrusters or control moment gyroscopes to satisfy excellent accuracy requirement is a challenging task. It becomes much more complicated for flexible spacecraft where thruster firings or some parts of control moment gyroscopes could excite flexible modals resulting in poor accuracy or even attitude control instability [2]. However, when attitude control requires small control operations, reaction wheels or momentum wheels will be used. It can provide continuous control torques according to the desired torque profile for attitude stabilization. In such case, thrusters or control moment gyroscopes should not be used any more, which will put forward higher requirements for the actuator.

During the past decades, considerable efforts have been made to study the attitude maneuver and vibration suppression of flexible spacecraft and the controller design theory has developed in a variety of directions. The adaptive control for rotational maneuver and vibration suppression of an orbiting flexible spacecraft has been presented in [3–5]. However, these literatures only considered the pitch angle and its derivative for feedback and flexible modes are not measured, which may cause parameter divergence and instability in the closed-loop system in front of unmodeled dynamics. Optimal control of flexible spacecraft has been considered in [6,7]. When we design such an attitude control law for spacecraft, it is desirable that the attitude control law guarantees not only robustness with respect to disturbances but also optimality with respect to a performance index. However, the two objectives are conflicting factors and a trade-off between them is needed. Based on Lyapunov function, the three-axis attitude tracking controller has been presented with robustness to parameter uncertainties and external disturbances for flexible spacecraft in [8]. The sliding mode fault tolerant control scheme has been developed in [9] in the presence of partial loss of actuator effectiveness fault and external disturbances. Despite several advantages, such as rapid response, low sensitivity to external perturbations and parameter variations, and low computational cost, sliding mode control has the chattering problem, which greatly hinders control precision. Based on the general sliding mode control, a new kind of sliding mode control technology named minimum sliding mode error feedback control (MSMEFC) has been proposed by Cao and Chen to tackle the problems of the uncertain disturbances [10–12]. MSMEFC has been used for fault tolerant control of spacecraft formation flying [10], fault tolerant control of

* Corresponding author.
E-mail addresses: liuchuangforever@msn.com (C. Liu), yed@hit.edu.cn (D. Ye), sunzhaowei@hit.edu.cn (Z. Sun).

http://dx.doi.org/10.1016/j.actaastro.2017.03.009
Received 16 July 2016; Accepted 10 March 2017
Available online 18 March 2017
0094-5765/

small satellite attitude [11] and satellite attitude control and determination [12]. The integrating variable structure control and modal velocity feedback technique has been proposed for flexible spacecraft attitude control and vibration suppression in [13], which has proven great potential for flexible spacecraft control. To achieve the attitude synchronization for a group of flexible spacecraft and the induced vibrations suppression during formation maneuvers, the distributed cooperative control strategy based on the backstepping design and the neighbor-based design rule was proposed in [14]. However, some problems have also been exposed in these integrated schemes, including complex algorithm structures and heavy computational burden. The fuzzy controller was designed in [15] for the attitude stabilization of the Republic of China Satellite (ROCSAT-1). Although this controller does not require gain settings and complicated computations, it is time consuming and cannot get satisfactory accuracy of the desired performance.

It is well known that H_2 control is often adopted to deal with transient performance while H_∞ control guarantees robust stability in the presence of parameter uncertainties and external disturbances. The mixed H_2/H_∞ controller can manage the trade-off between system performance and robustness, because it considers a mixed framework that can integrate optimal transient performance and robustness into a single controller. Consequently, it not only combines the merits of both H_2 optimal control and H_∞ robust control but also can achieve the suboptimal control performance under a desired disturbance rejection constraint. The mixed H_2/H_∞ control problems have been widely investigated by many researchers [16–19]. In [16], the mixed H_2/H_∞ control performance has been investigated compared with other methods such as PD control, H_2 control and H_∞ control for satellite attitude control system. In [17], the adaptive fuzzy mixed H_2/H_∞ control of nonlinear spacecraft systems was presented. Based on LMI approach, Ref. [18] applied mixed H_2/H_∞ state feedback controller to the microsatellite control and verified its good performance to achieve a balanced compromise between H_2 and H_∞ performances. The mixed H_2/H_∞ controller with a parameter adaptive law was presented in [19] for spacecraft attitude control. However, the mixed H_2/H_∞ controllers mentioned above just made the Lyapunov matrix variable involved in H_2 performance constraint equal to that involved in H_∞ performance constraint, so that the multi-objective integrated problem became a convex optimization problem with great conservatives. Thus, they can be called traditional mixed H_2/H_∞ controller. To reduce conservativeness, the Lyapunov variables introduced in H_2 performance and H_∞ performance constraint should be different. In other way, we can also eliminate the coupling of Lyapunov matrix variables and system matrices by introducing slack variable which provides additional degree of freedom. In this way, we can obtain the improved mixed H_2/H_∞ controller. In addition, to achieve satisfactory transients in the process of designing controllers, one has to place the closed-loop poles in a suitable region of the complex plane. About forty years ago, the pole allocation technique was proposed in [20] to allow controller designer to have direct control over the closed-loop system eigenvalues of flexible spacecraft. Recently, the poles placement theory in flexible spacecraft control has attracted great attentions. In [21], the control of a large flexible platform in orbit based on pole placement was studied. The pole placement technique combined with optimal control was used in [22] for vibration suppression during maneuver. However, to the best of our knowledge, the improved mixed H_2/H_∞ technique for flexible spacecraft attitude control and vibration suppression under poles assignment constraint has not been addressed, which is the focus of this paper. The main contribution of this paper is to design the robust high-precision attitude controller for flexible spacecraft with improved mixed H_2/H_∞ control strategy under poles assignment constraint. The proposed controller can simultaneously achieve attitude stabilization and vibration suppression. Actually, the robust mixed H_2/H_∞ control is one of the state feedback control methods. For state feedback control, all states of the system to be regulated were available to the controller, and it is complete feedback of system architecture information, while the static output feedback control is incomplete feedback of system architecture information. Thus, we want to test the difference of feedback performance and choose the static output feedback controller to compare with the robust mixed H_2/H_∞ controller.

The remainder of this paper is organized as follows. Section 2 establishes the state equations of flexible spacecraft dynamics and describes the purpose of this work. Section 3 proposes the design of robust H_2 and improved mixed H_2/H_∞ control under poles assignment constraint for flexible spacecraft system based on LMIs. Section 4 makes a detailed comparison analysis between improved mixed H_2/H_∞ controller under poles constraint and static output feedback controller in [23] by which this paper is motivated. Besides, the simulation results using traditional mixed H_2/H_∞ controller are also addressed. Finally, the concluding remarks and main references of this work are presented.

Notation: The superscripts "−1" and "T" mean matrix inverse and matrix transpose, respectively. R^n stands for the n-dimensional Euclidean space and diag([⋯]) means a block-diagonal matrix. Trace(·) denotes the trace of a matrix. $\|\cdot\|_2$ and $\|\cdot\|_\infty$ refer to 2-norm and ∞-norm for matrices, and α, β, γ, ρ, et al. stands for the mathematical expectation operator.

2. Problem statement

2.1. Flexible spacecraft dynamics

This section introduces the attitude model of a flexible spacecraft, which is described as a rigid body with two flexible appendages such as solar panels (see Fig. 1). The dynamical models of spacecraft are nonlinear and include rigid and flexible mode interaction. For flexible spacecraft with high-precision attitude control, the terminal three-dimensional rotations exist small values of the Euler angles, and the attitude system of the flexible spacecraft can be described by the following differential equations [24–26].

$$\begin{cases} J\ddot{\theta} + \Delta_1\ddot{\eta}_1 + \Delta_2\ddot{\eta}_2 = u + d \\ \ddot{\eta}_1 + 2\xi_1\Omega_1\dot{\eta}_1 + \Omega_1^2\eta_1 + \Delta_1^T\ddot{\theta} = 0 \\ \ddot{\eta}_2 + 2\xi_2\Omega_2\dot{\eta}_2 + \Omega_2^2\eta_2 + \Delta_2^T\ddot{\theta} = 0 \end{cases} \tag{1}$$

where J is the inertia matrix, θ is the spacecraft attitude angle vectors including yaw angle, pitch angle and roll angle, Δ_i (i=1,2) is the coupling coefficient matrix of ith solar panel, η_i (i=1,2) is the modal coordinate, ξ_i (i=1,2) and Ω_i (i=1,2) are the modal damping ratio and the modal frequency matrix corresponding to η_i, respectively, u is the control torque, and d represents the bounded disturbance torque.

Let $\hat{q} = [\theta^T \quad \eta_1^T \quad \eta_2^T]^T$, then Eq. (1) can be transformed into the following second-order matrix form:

$$R\ddot{\hat{q}} + H\dot{\hat{q}} + G\hat{q} = L_1u + L_2d \tag{2}$$

where,

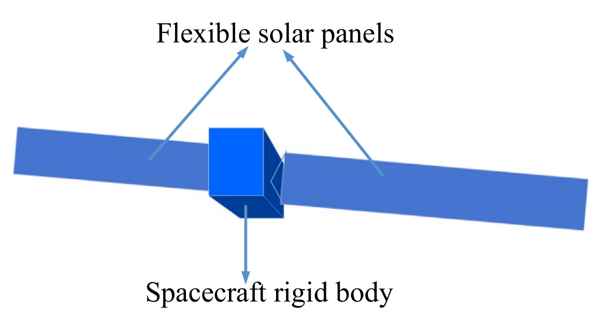

Fig. 1. Configuration of a flexible spacecraft.