Acta Astronautica 67 (2010) 572–583

Contents lists available at ScienceDirect

Acta Astronautica

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

Sliding mode attitude control with L_2-gain performance and vibration reduction of flexible spacecraft with actuator dynamics

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ARTICLE INFO

Article history:
Received 14 October 2009
Received in revised form
6 April 2010
Accepted 21 April 2010
Available online 18 May 2010

Keywords:
Sliding mode control
Flexible spacecraft
Vibration reduction
Attitude maneuver
Actuator dynamics

ABSTRACT

This paper presents a dual-stage control system design method for the rotational maneuver control and vibration stabilization of a flexible spacecraft. In this design approach, the sub-systems of attitude control and vibration suppression are designed separately using the low order model. Based on the sliding mode control (SMC) theory, 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, incorporating the L_2-gain performance criterion constraint. The resulting closed-loop system is proven to be uniformly ultimately bounded stability and the effect of the external disturbance on both attitude quaternion and angular velocity can be attenuated to the prescribed level as well. In addition, an adaptive version of the control law is designed for adapting the unknown upper bounds of the lumped disturbance such that the limitation of knowing the bound of the disturbance in advance is released. For actively suppressing the induced vibration, strain rate feedback control method is also investigated by using piezoelectric materials as additional sensors and actuators bonded on the surface of the flexible appendages. Numerical simulations are performed to show that rotational maneuver and vibration suppression are accomplished in spite of the presence of disturbance and uncertainty.

1. Introduction

One of the most important problems in spacecraft design is that of attitude stabilization and control. Although the missions of space vehicles and their attitude requirements vary greatly, high pointing accuracy is an important part of the overall design problem for a spacecraft control system. Meeting the spacecraft attitude control system design requirements in a realistic environment where the knowledge about the system parameters may be incomplete, disturbances are present and orbital operations induces structural vibrations in the flexible appendages, is a challenging task for the designers.

Significant research efforts have addressed the problem of stabilization and performance of spacecraft attitude control system. Based on a linear approximation to a nonlinear system model, classical robust control approaches based on linear control theory were employed for spacecraft attitude control problem and many publications have shown that these linear control approaches might be successfully applied to spacecraft even with parameter uncertainty problems [1,2]. For most situations, this assumption needed for linear approximation for space vehicles is not valid. Therefore, robust adaptive control techniques attract more attentions [3–5] in which the actual model is not needed. Optimal and nonlinear control systems for the control of flexible spacecraft have also been developed in Refs. [6,7]. A nonlinear controller based on neural network for nonlinear slew maneuver of flexible spacecraft has been designed using state feedback [8]. Based on sliding mode control (SMC) theory, several representative works [9–16] on this topic are available in the literatures. For different mission objectives [9–11], various control techniques have been developed and compared. However, in most of these studies concerning

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doi:10.1016/j.actaastro.2010.04.018

SMC, it is assumed that the spacecraft is rigid and no flexible mode actions are considered. For the flexible spacecraft model, finite mathematical discretization was used to design sliding mode controllers and there have been significant research efforts for the general feedback attitude control of flexible spacecraft [12–14]. In a practical situation, the measurements of flexible modes are extremely difficult. Thus, there is a need to design a control system for torque control which does not require the measurement of all state variables. Based on output feedback control concept, controllers for maneuvering the flexible spacecraft have been designed in the presence of uncertainties and external disturbances in Refs. [15,16].

A typical feature in all of the mentioned attitude control schemes is that these controllers are designed for control torque and no actuator dynamics is considered in the control system design. Even if these controllers may be applied to torque device such as thruster or reaction wheel in torque mode, in real applications, on-time thruster or reaction wheel input voltage is very important because system response directly depends on it. For the spacecraft equipped with momentum exchange devices, there is momentum exchange between spacecraft system and reaction wheel system without changing overall inertial angular momentum. The angular momentum generated by the reaction wheel is transferred to the spacecraft system and the momentum generated by spacecraft rotation affects reaction wheel system. Therefore, the controller design with actuator dynamics should be considered for real applications. Even if there are many relative research works on robotic control problem [17,18], there are few research works found for this area, which was acknowledged by the author.

On the other hand, the orbital maneuvering/slewing operations will introduce vibrations to the flexible structures to some degree. To reduce the induced vibrations the use of piezoelectric materials with advanced control algorithms are investigated as a potential solution. Numerous researchers have focused on vibration control of flexible structures associated with the piezoelectric materials. Bailey and Hubbard [19] proposed simple but effective control algorithms for transient-vibration control, constant amplitude control and constant gain control. Baz and Poh [20] worked on the vibration control of the smart structures via a modified independent modal space control by considering the effect of the bonding layer between the piezoelectric material and the host structure. Tzou [21] investigated the piezoelectric effect on the vibration control through a modal shape analysis. Positive position feedback (PPF) was also proposed in Ref. [22] and then extended in Ref. [23]. Applications using strain rate feedback (SRF) control, in which by feeding the structural velocity coordinate information directly to a compensator and the compensator position coordinate, multiplied by a negative gain, is fed back to the structure, can also be found in areas including the vibration control of flexible systems [24].

The contribution of this work lies in the derivation of active vibration control technique integrated with a robust adaptive control law with L_2-gain performance for attitude control and vibration reduction in the presence of external disturbances and uncertainties. The design approach presented here treats the problem of spacecraft attitude control separately from the elastic mode vibration suppression problem, and is a dual-stage control system method. Based on the sliding mode control (SMC) theory, a discontinuous control law is derived, and the control performance is evaluated by L_2-gain constraint with disturbance attenuation on both attitude quaternion and angular velocity. Lyapunov's argument is used to show that uniformly ultimately bounded stability with the L_2-gain less than a given small level is ensured. Furthermore, the developed attitude controller is expanded through adaptive control technique without the limitation of knowing the bounds of perturbation in advance, that is, an adaptive sliding mode attitude controller is proposed. In addition, for eliminating the chattering, a smooth control signal containing hyperbolic tangent function is adopted instead of the sign function. The advantage of this dual-stage approach is that once the desired orientation is attained under the SMC law, only the elastic motion is governed by the decoupled linear second-order systems describing elastic dynamics. For the actively damping of the elastic motion, strain rate feedback control method is also employed for actively damping the elastic oscillations using piezoelectric materials as additional sensors and actuators bonded on the surface of the flexible appendages. Finally, applications are carried out on a flexible spacecraft. The paper is organized as follows. The next section states flexible spacecraft modeling, the actuator dynamics and attitude control problem. Attitude control laws based on SMC and adaptive SMC with L_2-gain performance are derived in Section 3 and the active vibration compensator design is shown in Section 4. Next the results of numerical simulations demonstrate various features of the proposed control law. Finally, the paper is completed with some concluding comments.

2. Mathematical model and control problem

2.1. Mathematical model of a flexible spacecraft

Attitude kinematics represented by four unitary quaternions is given as follows [9]:

$$\begin{bmatrix} \dot{q}_0 \\ \dot{q} \end{bmatrix} = 1/2\mathcal{Q}^T(q_0,q)\omega \tag{1}$$

where $q_0=\cos(\Phi/2)$ and $q=[q_1\ \ q_2\ \ q_3]^T=\mathrm{X}\sin(\Phi/2)$ are subject to the constraint $q_0^2+q^Tq=1$. Here Φ denotes the rotation angle about the Euler axis, which is determined by the unitary vector X, $(q_0,q)=[-q,q_0I-[q\times]]$ with $[q\times]$ satisfying

$$[q\times]=\begin{bmatrix} 0 & -q_3 & q_2 \\ q_3 & 0 & -q_1 \\ -q_2 & q_1 & 0 \end{bmatrix} \tag{2}$$

and ω the angular velocity of the unformed spacecraft in the body fixed frame. This description of the orientation avoids the geometric singularities inherent with three parameter descriptions (Euler angles, etc.).