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Robust integral variable structure controller and pulse-width pulse-frequency modulated input shaper design for flexible spacecraft with mismatched uncertainty/disturbance

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Abstract

This paper presents a dual-stage control system design method for the flexible spacecraft attitude maneuvering control by use of on–off thrusters and active vibration control by input shaper. In this design approach, attitude control system and vibration suppression were designed separately using lower order model. As a stepping stone, an integral variable structure controller with the assumption of knowing the upper bounds of the mismatched lumped perturbation has been designed which ensures exponential convergence of attitude angle and angular velocity in the presence of bounded uncertainty/disturbances. To reconstruct estimates of the system states for use in a full information variable structure control law, an asymptotic variable structure observer is also employed. In addition, the thruster output is modulated in pulse-width pulse-frequency so that the output profile is similar to the continuous control histories. For actively suppressing the induced vibration, the input shaping technique is used to modify the existing command so that less vibration will be caused by the command itself, which only requires information about the vibration frequency and damping of the closed-loop system. The rationale behind this hybrid control scheme is that the integral variable structure controller can achieve good precision pointing, even in the presence of uncertainties/disturbances, whereas the shaped input attenuator is applied to actively suppress the undesirable vibrations excited by the rapid maneuvers. Simulation results for the spacecraft model show precise attitude control and vibration suppression.

Keywords: Vibration suppression; Input shaping; Flexible spacecraft; Integral variable structure control (IVSC); Observer; Attitude maneuver

1. Introduction

Fine attitude control and stabilization are the key technologies of modern flexible spacecrafts, whose missions, such as re-pointing and tracking maneuver, require high pointing accuracy and stabilization. However, the orbiting attitude slewing or maneuvering operation will introduce certain levels of vibration to flexible appendages, which will deteriorate its pointing performance. In addition, dynamics of large rotational maneuvers are time varying and nonlinear, they are affected by various disturbances coming from the environment and knowledge about system parameters such as inertia matrix and modal frequencies is usually unknown. Therefore, disturbance rejection control strategies that are also robust to parametric uncertainty and effectively suppress the induced vibration are of great interest in spacecraft applications.

Active control techniques have been increasingly used as the solutions for flexible spacecrafts to achieve the degree of vibration suppression for required precision pointing. One of the techniques that can be used for vibration suppression is the input shaping [1–9], which works by exploiting the convolution of the reference signal with a sequence of impulses to reduce the system vibrations. This scheme was first introduced in Smith's work on posicast control [1], and later Singer and Seering [2] ameliorated this control strategy by introducing robustness into the shaper to variations in estimated damping and frequency. This was achieved by increasing the number of discrete steps, from the two proposed by Smith to three or more: the greater the number of steps, the greater the robustness. Singhose et al. [3] studied an

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input shaping controller for slewing a flexible spacecraft. Banerjee and Padereiro [4] proposed the application of input shaping for vibration reduction of flexible spacecraft following momentum damping with/without slewing. Using pulse-width pulse-frequency modulation technique, Song et al. [5] treated the application of input shaping for vibration reduction of a flexible spacecraft. Nonlinear input shaping technique was considered by Gorinevsky and Vukovich [6] for the flexible spacecraft reorientation maneuver. There are also several papers reporting experimental verifications of those techniques. In Ref. [7], the results were discussed of the application of input shaping on the MACE experiment, which flew on the space shuttle in 1995. In Refs. [8,9], the experimental testing of command shaping techniques on flexible link manipulator was also reported. Other approaches have also been developed for active control of flexible spacecraft. Active damping technique for satellites with flexible appendages by rate feedback using observer was utilized in Ref. [10]. Teague et al. [11] presented an active control attitude and vibration of flexible spacecraft using the global positioning system (GPS), and the experimental results showed its effectiveness. A dynamic controller with piezoelectric actuator for large angle maneuver of flexible spacecraft was designed in Refs. [12, 13]. Song and Agrawal [14] also considered using smart materials for vibration suppression and pulse-width pulse-frequency modulator for thruster firing for the attitude control during attitude maneuver. Other motivations and benefits in the use of active control technology can also be found in Ref. [15], which provides a good source of reference.

A second critical problem, which often affects flexible spacecraft, in addition to structural flexibility, is the model uncertainties. The flexible spacecraft is governed by a partial differential equation (PDE) as a system of distributed-parameter and therefore possesses infinite number of dimensions, which makes it difficult to control. Controller design for flexible spacecraft is in general based on an approximated finite-dimensional model by truncating the infinite number of modes to a finite number through neglecting the higher frequency modes. Model inaccuracies can have a strong adverse effect on flexible dynamics system. Variable structure control (VSC) is known to be an efficient control technique applicable to systems with profound nonlinearity and modeling uncertainty [16,17]. The controller design is based upon the sliding surface on which system states remain while converging to an equilibrium state. The sliding surface is a pre-determined manifold to prescribe the trajectory of state variables by active control action. The controller is constructed in a way to drive the system states into the sliding surface from an arbitrary initial state. General sliding mode controllers, therefore, consist of terms handling system nonlinearities and feedback to guarantee the stability of the closed-loop system. A tutorial and survey on variable structure control can be found in Ref. [16]. A comprehensive guide on sliding mode control for control engineers was given in Ref. [17]. VSC is also greatly interesting to the people in the field of spacecraft attitude control research [18–20] because of its fast dynamic control, global asymptotic stability, invariability for interference perturbation. Moreover, VSC represents a systematic approach to the design of on/off control laws for multivariable systems, which is a good match to the thruster actuator mode commonly used in a satellite. Recently, a control scheme called integral variable structure control (IVSC) has been studied by several researchers [21–23]; in which an integral controller is added to a variable structure controller, so that not only the uncertainties, parametric variations and disturbances can be rejected, but also resulted in zero steady-state error under step input. However, all of the state variables of the system must be accessible to the control law. In practical application, full measurement of state might be neither possible nor feasible, such as the measure of the variables describing the flexible motion, the modal position, and velocity of the flexible spacecrafts. In this case, a full-state feedback variable structure controller cannot be implemented unless an observer is used to estimate the unmeasured states, or the design methods must be notified such that only a subset of the states is required to implement the control law. The design of asymptotic observers has been used in VSC to deal with the unavailability of states [24,25]. In addition, in all these results, it is required that the uncertainty/disturbance considered is matched, i.e., acts in the channels of the inputs. In many cases, however, this matching condition can hardly be satisfied, if not impossible. There have been several papers reporting variable structure control technique for the mismatched uncertainty/disturbance [26,27]. The study of invariable variable structure control for a flexible spacecraft containing mismatched uncertainty/disturbance has not been adequately addressed or discussed in the literature.

This paper explores an approach to design a control system such that attitude rotational maneuvers can be performed in spite of the presence of mismatched bounded disturbances torque/model uncertainty and the elastic oscillations caused due to slewing can be actively reduced as well. Although the design approach is applicable to spacecrafts of other configurations, for definiteness, an orbiting spacecraft consisting of a rigid hub with two flexible appendages is considered for design. The proposed control design process is two fold: design of the attitude controller using IVSC principle followed by a flexible vibration controller. The attitude controller design for the spacecraft motion requires selection of a hyperplane in state space which produces the desired dynamics, such that the selected hyperplane is a globally attractive manifold and leads to a sliding mode. When the system in the sliding mode, the dynamic equations of the closed-loop system can be reduced to a linear form and its eigenvalues can be arbitrarily assigned. Lyapunov stability analysis shows that the proposed control guarantees exponential convergence of attitude angle and angular velocity in the presence of bounded uncertainty/disturbances. Because not all of the states are available for the control of the flexible spacecraft, a variable structure observer is employed to estimate the unavailable states. In the presence of the attitude controller, the input shaping technique is used to modify the existing command so that less vibration will be caused by the command itself, which only requires information about the vibration frequency and damping of the closed-loop system. Additionally, in order to efficiently convert the continuous input commands into on–off