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Synthesis of a linearly interpolated gain scheduling controller for large flexible spacecraft ETS-VIII

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ABSTRACT

This paper illustrates a design procedure for a linearly interpolated gain scheduling controller for Engineering Test Satellite VIII (ETS-VIII) using its linear parameter-varying (LPV) model. The LPV model here consists of piecewise-linear functions of the paddle rotation angle and a norm-bounded perturbation. The main purpose of this research is to derive a simple structured scheduling law that can be easily implemented in a satellite onboard computer. The derived gain has only two grid points and is scheduled simply by linear interpolation, which is desirable from the standpoint of implementability. Moreover, since the synthesis condition is based on parameter-dependent Lyapunov functions, it gives less conservative results than existing methods. Simulation results are presented to show the effectiveness of the proposed synthesis.

1. Introduction

Satellites have become important to daily life, for broadcasting, communications, weather forecasting and so forth. To meet ever more demanding mission requirements, satellites are growing in size, and large flexible components such as communication antennas are inevitably appended. One of the major difficulties in controlling a large flexible satellite is the "spillover" phenomenon (Balas, 1978), a system instability due to the structural vibrations of flexible components such as solar paddles and antenna reflectors. These difficulties have been studied in many research papers and some modern control synthesis methods have been applied in recent studies (Charbonnel, 2004; Chiappa, Bodineau, Boulade, & Beugnon, 2005), where the common challenge has been to control the attitude of satellites precisely and robustly against parameter variations of the vibration dynamics. These vary due to, for example, the rotations of the solar paddles to keep them facing the sun.

On-orbit attitude and vibration control experiments on satellites with large flexible components have also been conducted during the past two decades (Bukley, 1995; Grocott, How, MacMartin, & Liu, 1994). In Japan, Engineering Test Satellite VI (ETS-VI), a three-axis stabilized geosynchronous satellite with a pair of large lightweight solar paddles, was used for such experiments (Kida & Yamaguchi, 1997). Some modern control techniques including H_∞ control theory were tested in the experiments and then proved useful for flexible satellite control. Although these were successful, some research issues remain. One of these is controller design as a linear parameter-varying (LPV) system, which is defined as a linear time-varying system whose state-space matrices are fixed functions of varying parameters. Since the solar array paddles constantly rotate, the system model varies drastically according to their rotation angle and is described as an LPV system with paddle rotation angle as a varying parameter. In the original ETS-VI experiments, a "paddle-fixed frame" was introduced to the control system to get around the satellite model's dependency on paddle rotation. However, this method is applicable only when the satellite's moments of inertia around the two axes apart from the paddle rotation axis are almost equal, and is therefore not always suitable.

Gain scheduling control techniques have been considered applicable to and useful for LPV systems, and many studies of gain scheduling controller design have been carried out during the past two decades (for example, Apkarian & Gahinet, 1995; Becker & Packard, 1991; Lim, 1999; Stilwell & Rugh, 2000; Wu, Yang, Packard, & Becker, 1996). In order to apply gain scheduling control techniques to satellites, which have only limited onboard computational resources, the control program must be small. In the ETS-VI experiments, for example, only a 3 kbyte area of the onboard computer's memory was available for the control program. In addition, the scheduling law should not require complex calculations because of low onboard computer performance. Thus, it is difficult to employ directly scheduling laws that require a matrix inverse calculation at each scheduling parameter value;

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for example the scheduling laws derived in Wu and Kim (2002) and Stilwell and Rugh (2000).

One possible way to use gain scheduling control is to introduce parameter grid points and approximate the complex scheduling laws by piecewise-linear functions between grid points. Although this avoids computing matrix inversions, another question arises: Is stability guaranteed between the grid points? Stability becomes suspect particularly when the approximation error of the implemented controller is somewhat large. Although the approximation error can of course be reduced by introducing a large number of grid points, stability cannot be guaranteed automatically. Moreover, a large number of grid points require more onboard computer memory, which is not always acceptable for satellite systems.

Another possible way is to design simply structured gain scheduling controllers directly. This can be done using the synthesis methods in Apkarian, Gahinet, and Becker (1995), for example, with parameter-independent Lyapunov functions, which leads to rather conservative performance as described in Apkarian and Adams (1998). These deficiencies considered, a synthesis method that yields piecewise-linear scheduling laws directly with parameter-dependent Lyapunov functions would be attractive to satellite controller designers. In fact, as a state feedback case, such a synthesis method was developed in a previous research (Hamada, Yamaguchi, & Kida, 2005). However, this method cannot be used directly for satellite attitude control because state feedback is not available since not all the states can be observed.

This paper illustrates a design procedure of a linearly interpolated gain scheduling controller for Engineering Test Satellite VIII (ETS-VIII). The satellite, with a gross weight of around three tons and a diameter of 40 m, was launched in 2006 by Japan's H-IIA launch vehicle No. 11. It was developed primarily to establish and validate the world's largest geostationary satellite bus technology with the main purpose of handling the increasing demand for digital communications from mobile telephones and other mobile devices. The satellite has four large flexible appendages: a pair of deployable antenna reflectors and a pair of solar array paddles (Fig. 1). The proposed synthesis method is suitable for satellite control systems because it yields a simple output feedback scheduling law that consists of a small number of grid points and requires only linear interpolation. The synthesis condition can be described in the linear matrix inequality (LMI) form with a line search parameter, and so the offline computational cost is not so demanding. The derived controller guarantees stability and performance not only at each grid point of the controller but for all scheduling parameter values. In addition, the synthesis condition is based on parameter-dependent Lyapunov functions which lead to much less conservative results. The derived controller is therefore expected to achieve the objective of low computational burden combined with good control performance. To apply the synthesis condition, an LPV model of ETS-VIII is described by approximating system matrices using piecewise-linear functions of the parameter (i.e. paddle rotation angle). Approximation errors are taken into account in the controller design by modeling them as a norm-bounded perturbation.

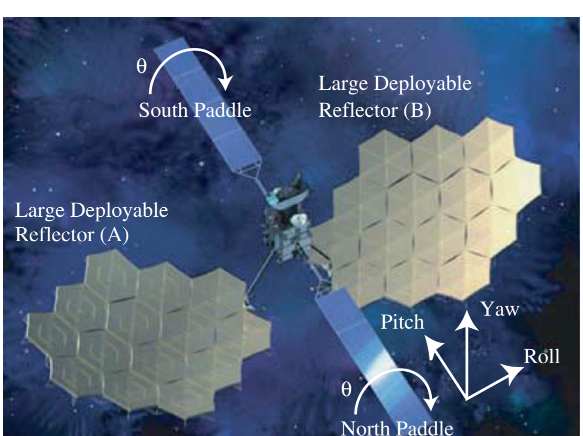

Fig. 1. Conceptual image of ETS-VIII and its coordinates.

This paper is organized as follows. The ETS-VIII satellite model is described as an LPV system in Section 2. Section 3 illustrates the controller design procedure for ETS-VIII using the proposed synthesis and compares it with existing methods. The results of simulations are also presented that demonstrate the effectiveness of the designed controller in Section 4.

2. Models of the ETS-VIII spacecraft

This section presents some model descriptions of ETS-VIII. The so-called *constrained mode model*, which is commonly used for describing flexible satellite dynamics, is given by the rigid-body rotation and vibration equations. Although some controller design methods can deal with this model directly (Nagashio, Kida, Ohtani, & Hamada, 2010), this sometimes leads to rather high order controllers when a full order controller design method, such as H_∞ controller design, is applied. One way to avoid high order controllers is to reduce the order of the satellite model. The *unconstrained mode model* is then preferable because it becomes easy to distinguish lower vibration modes from higher ones. In addition, these can be easily decoupled and the *reduced order model* is derived straightforwardly. Finally, the *LPV description using piecewise-linear approximation* is derived from the reduced order model in order to obtain a linearly interpolated gain scheduling controller.

2.1. Constrained mode model

As is mentioned above, ETS-VIII has two large deployable antenna reflectors and two solar array paddles which are deployed in the pitch direction and rotate 360 deg each day so that each wing constantly faces the sun. These components are supposed to be aggregated, articulated flexible bodies. Since the paddle rotation speed is 4.17×10^{-3} deg/s (=360 deg/day), which is sufficiently slow, the equation of motion for rigid-body rotation and the vibration equation of the flexible components of a large flexible satellite are as described in (Hughes, 1980; Likins, 1970; Sidi, 1997):

$$J(\theta)\ddot{\Psi}+\sum_j P_j(\theta)\ddot{\mu}^{(j)}=u, \tag{1}$$

$$P_j^T(\theta)\ddot{\Psi}+\ddot{\mu}^{(j)}+\Omega_j^2\mu^{(j)}=0 \quad (j=n,s,a,b), \tag{2}$$

In these equations, the script $j=\{n,s,a,b\}$ denotes the north/south solar paddles and the A/B antenna reflectors respectively. $\mu^{(j)}\in\boldsymbol{R}^{n_\nu(j)\times1}$ is the modal coordinate of each flexible component with $n_\nu(j)$ vibration modes $(n_\nu(n)=n_\nu(s)=n_\nu(a)=n_\nu(b)=8)$. $\Psi\in\boldsymbol{R}^{3\times1}$ is the attitude angle vector and $\Omega_j\in\boldsymbol{R}^{n_\nu(j)\times n_\nu(j)}$ is the modal stiffness. $J(\theta)\in\boldsymbol{R}^{3\times3}$ denotes the rotational inertia of the satellite and $P_j(\theta)\in\boldsymbol{R}^{3\times n_\nu(j)}$ represents the interaction between rotation and vibration. Since ETS-VIII is a geosynchronous satellite at an altitude of approximately 35,786 km, gravitational gradient torques are negligible and are therefore omitted here. The input $u\in\boldsymbol{R}^{3\times1}$ is a control torque for each axis produced by reaction wheels. The output $y\in\boldsymbol{R}^{6\times1}$ consists of the attitude angles and rate vectors, which are estimated by attitude determination logic