Study of Robust Feedback Controller for Agile and Flexible Spacecraft “ASTRO-G”

柔軟構造を有する人工衛星 “ASTRO-G” のための高速姿勢制御の一検討

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ASTRO-G will be launched for VSOP (VLBI Space Observatory Program)-2. ASTRO-G have to maneuver the attitude between target celestial-object and quasar alternately and quickly, because VLBI observation requires calibration for phase fluctuations of atmosphere which changes fast. In addition, ASTRO-G will have a huge antenna to compose VLBI, which is a flexible structure and difficult to model. Therefore, in the ASTRO-G mission, attitude control system have to satisfy these challenging requirement: Agile maneuvering and flexible structures.

In the current strategy of the attitude control system, feedforward control is mainly applied to ASTRO-G mission. In this strategy, reference called NME “(Nil-Mode-Exciting) profiler” is proposed by Toshio Kamiya et al. to excite no flexible modes in agile maneuver. Authors, however, are concerned about unexpected disturbance, characteristics of actuators and sensors, noise and so on. On the other hand, feedback control is desirable because it can have robustness against unexpected disturbance.

In this paper, we studied whether feedback control is applicable for ASTRO-G mission. 2DOF (Degree Of Freedom) control is applied to ASTRO-G’s attitude control system: Robust $H_\infty$ control and NME profiler. The simulation results show the effectiveness of 2DOF control system for the agile maneuvering with flexible structures.
I. Introduction

A. Background of Research

A radio telescope satellite “ASTRO-G” is expected to be launched in 2012 for VSOP (VLBI Space Observatory Program)-2. VSOP-2 is a space VLBI mission, which expands VLBI observation to space. Since the resolution in VLBI observation is proportional to baseline (the length between antennas), cooperation among ground radio telescopes and ASTRO-G’s antenna can attain such a high resolution that only ground radio telescopes never attain. Overviews of VLBI switching observation and VSOP are shown in Figs. 1 and 2.

Since ground radio telescopes require calibration of phase fluctuation by air in VSOP-2 mission, all antenna is required to observe target celestial object and quasar for calibration alternately in one minute cycle. ASTRO-G realize this fast switching observation by attitude maneuvering. Therefore, ASTRO-G have to maneuver in order that the loaded antenna may orient two celestial objects alternately. The switching observation requires ASTRO-G’s attitude control system to maneuver 3 deg and to converge attitude angle error within ±0.002 deg in 15 sec.

In addition, the antenna loaded into ASTRO-G should be treated as flexible structure. The 8 m diameter antenna is too huge to identify its modal parameter exactly. Because of this reason, robust control theory is desirable to feedback control system. Therefore, ASTRO-G’s control system is required to have both robustness to modeling error and fast transient response performance.

B. Purpose of This Research

ASTRO-G’s attitude control system is now researched in cooperation with a satellite manufacturing company. Current control system strategy is to design feedforward reference that excites no flexible modes, called Nil-Mode-Exciting (NME) profiler. Because NME profiler is designed by using sinc function which doesn’t have frequency component over its cutoff frequency, feedforward control with NME profiler is considered to work out.

Authors, however, have anxiety of feedforward main control designing. For example, ASTRO-G will load CMGs as actuator, which rarely used in past satellites. It is anxious if CMGs excite some flexible modes, and if VLBI observation cannot be done because of this excited vibration. Therefore, whether feedback control is applicable or not is examined in this paper.

II. Modeling of Satellite Attitude System

A. Equation of Motion

Motion equation of satellite attitude is represented as simultaneous equation consists of rigid body motion equation and flexible part motion equation.

\[ I\ddot{\theta} + Q^T \dot{\eta} = T \]  

(1)
\[
\ddot{\eta} + 2\zeta \sigma \dot{\eta} + \sigma^2 \eta + Q \ddot{\theta} = 0
\]  

(2)

where \(\theta, \eta, T\) are attitude angle, flexible variable, and torque respectively. \(I, \zeta, \sigma, Q\) are moment of inertia, damping matrix, stiffness matrix, and interference matrix respectively. Controlled variable and observable variable is attitude angle \(\theta\), and control input is torque \(T\). After coordinate transformation for decoupling flexible modes, transfer function can be written as eq.(3)

\[
P(s) = \frac{\Theta(s)}{T(s)} = \frac{1}{Is^2} + \sum_{i=1}^{N} \frac{\phi_i^2}{s^2 + 2\zeta_i \omega_i s + \omega_i^2}
\]  

(3)

Plant can be written as three transfer functions: x-axis, y-axis, and z-axis transfer functions. Although actual system has three-axis interference, ASTRO-G has the features listed below.

1. Since z-axis (= antenna axis) rotation doesn’t effect the VLBI observation, z-axis rotation can be ignored
2. The interference between x-axis and y-axis is negligible

Because of these features, SISO controller was made in this paper. Figure 3 shows bode diagram of x-axis plant.

### B. Modeling Error

In general, model identification of flexible structures is getting harder as the eigen frequency of the flexible modes goes higher, and modeling error becomes more considerable. The flexible appendages loaded into satellite are a 8 m diameter antenna and a solar paddle. Because of their own weight, these flexible structures cannot maintain their shapes without any support. Therefore, parameter identification would be done with partial structures of flexible structures. Then, the characteristics of the whole flexible structures would be numerically synthesized. After launching, modal parameters would be identified by shaking test on-orbit. These two model identifications, i.e. on the ground and on-orbit identification, differs from each other. The difference between ground identification and on-orbit identification in eigen frequency was about 20% at a maximum. Therefore, feedback control system should be robust to modeling error of modal parameters.

### III. 2 DOF Control System

#### A. Robust Feedback Control

In this paper, \(H_\infty\) control was applied as robust feedback control. Figure 4 shows generalized plant to synthesis \(H_\infty\) controller. A stabilizing controller \(C\) could be obtained by designing singular value of weighting function \(W_t\) larger than conceivable perturbation \(\Delta\), and \(||G_{\omega_z}||_\infty < 1\).

1. Guidance for Controller Synthesis

In general, lower flexible modes can be identified almost exactly. In this paper, the lowest mode was included in nominal plant, and the other flexible modes were represented as additive perturbation. This is considered not very challenging controller synthesis, because Engineering Test Satellite (ETS)-6 demonstrated \(H_\infty\) controller synthesis that include the lowest flexible mode as nominal plant. There are two constraints when designing attitude controller of ASTRO-G. First, calculator performance on board should be considered because the performance is not very high. Hence, the order of controller is limited.
Therefore, nominal plant and weighting function should be decided with consideration of their order. Second, sampling frequency of attitude control calculator should be considered. Under current strategy of attitude control system, the sampling frequency is considered to be 32 Hz. Hence, there is a region on s-plane the poles of controller should be.

2. Synthesis of $H_\infty$ Controller

$H_\infty$ controller was synthesized based on the guidelines mentioned above. Nominal plant includes the lowest flexible mode, and represented as eq. (4)

$$P_n(s) = \frac{1}{Is^2} + \frac{\phi^2_1}{s^2 + 2\zeta_1\omega_1 s + \omega_1^2}$$

Figure 5 shows weighing function $W_t$ for robustness. Weighting function $W_t$ is designed that singular value of $W_t$ is to cover over singular value of additive perturbation $\Delta$. Hereby, robust controller which stabilize if high order modes have modeling error, can be obtained. Weighting function $W_s$ for sensitivity function is designed as four order low pass filter, in consideration of order of synthesized controller. Taking into account of constraint about sampling frequency of attitude control calculator, controller is designed with pole placement constraint by LMI.

3. Simulation Result of Closed-Loop System

Numerical simulation was done with closed-loop system which consists of synthesized $H_\infty$ controller and full-order plant. Full-order plant consists of rigid mode, eight flexible modes of antenna, and four flexible modes of solar paddle. Step response to the closed-loop was shown in Fig. 6. $H_\infty$ controller was discretized by 32 Hz tustin conversion. A vibration can be seen in Fig. 6 from 5 sec to 20 sec. The frequency of this vibration corresponds to 1st flexible mode which is included in nominal plant when $H_\infty$ controller was synthesized. Figure 7 shows the frequency characteristics of the controller and plant. The notch effect of the controller correspond to 1st flexible mode is different in the respect of frequency. This is due to LMI pole placement constraint in the $H_\infty$ control synthesis.

B. Feedforward System Designing

In this section, feedforward control system was designed. To design feedforward control, reference called NME (Nil-Mode-Exciting) profiler was used. Figure 8 shows block diagram of 2 DOF control system. In this paper, reference is given as torque dimension.

Nominal plant in Fig. 8 was studied after simulation. For a time, nominal plant was considered to be rigid mode and 1st flexible mode, and represented as eq. (5)

$$P_n = \frac{1}{Is^2} + \frac{\phi^2_1}{s^2 + 2\zeta_1\omega_1 s + \omega_1^2}$$

1. NME Profiler
The reference $R$ of 2 DOF control was designed by NME profiler. Subsequent paragraphs show concept and design procedure of NME profiler.

**CONCEPT OF NME PROFILER**  The concept of NME profiler is to excite no flexible modes. NME profiler is based on sinc function represented as eq. (6)

$$x(t) = \frac{\sin(\omega_s t)}{\omega_s t}$$

(6)

Sinc function doesn’t have frequency component higher than cut off frequency $\omega_s$ rad/sec. Hence, being designed $\omega_s$ lower than the eigen frequency of the lowest flexible modes, the sinc function excites no flexible modes.

**DESIGNING PROCEDURE OF NME PROFILER**  The designing procedure of NME profiler is listed as blow.

1. Adding two sinc functions: sinc function for acceleration and deceleration
2. Multiplying the result of (1) and a hamming window in time domain

Figure 9 shows sinc functions for acceleration and deceleration, and Fig. 10 shows hamming window. Hamming window was multiplied because sinc function have infinity time section. In the cause of windowing, NME profiler have some frequency component over $\omega_s$, the cut off frequency of sinc function. However, effect of windowing is negligible, i.e. frequency component of NME profiler over cut off frequency can be ignored. Thus, NME profiler can be mentioned as reference which excites no flexible modes.

**C. Numerical Simulation**

This section shows the results of numerical simulations of designed 2 DOF control system consists of $H_\infty$ feedback controller and NME profiler. Block diagram of 2DOF system is shown in Fig. 8. Feedback controller $C$ was $H_\infty$ controller designed in section 2 nominal plant in 2 DOF system was rigid mode $\frac{1}{s^2}$, and reference $R$ was NME profiler. Controlled plant includes rigid mode and twelve flexible modes.

First, simulation with nominal plant was done. Figure 11 shows the result of attitude angle. As illustrated in Fig. 11, attitude angle converge within $3 \pm 0.005$ deg about 16 or 17 sec. This result almost satisfy the mission demand.

Next, simulation with perturbed plant was done. In this simulation, frequency of all flexible modes are designed to be (1) nominal values, (2) 0.8 times of nominal values, (3) 0.9 times of nominal values, and (4) 1.2 times of nominal values. Figure 12 shows the results of simulation. As illustrated in Fig. 12, the worst case was when frequency error was 20% lower than nominal values. In this worst case, however, the control system has stability and convergence attitude angle about 20 sec.

Finally, feedforward controller was studied with simulation. In this simulation, how many flexible modes nominal plant in feedforward controller $\frac{1}{P_n}$ should include, was studied. Simulation cases are that (1) $P_n$ was...
only rigid mode, (2) \( P_n \) was rigid mode and 1st flexible mode, and (3) \( P_n \) was rigid mode and 1st, 2nd, and 3rd flexible mode. Fig. 13 shows the simulation results of these cases. Compared to case (1), convergence time of case (2) is short. However, case (3) had the same convergence time as case (2). Therefore, we concluded that nominal plant in feedforward controller \( P_n \) should be rigid mode and 1st flexible mode.

IV. Conclusion

VSOP-2 project was introduced, and robust and agile control system demand was explained. 2 DOF control system with \( H_\infty \) feedback control and NME profiler was designed to fulfill the mission demand. By numerical simulation, effectiveness of the designed 2 DOF control was shown. Because feedback controller was designed by \( H_\infty \) control theory, the closed-loop doesn’t lose stability if modeling error of eigen frequency of flexible modes was about 20%. Because, the designed 2 DOF control system had robustness and fast transient response, applicability of feedback control was shown.

References

1VSOP-2 Project: http://www.vsop.isas.ac.jp/vsop2e/


