A Study of High-Speed and High-Precision Attitude Control for Flexible Satellite ASTRO-G in Consideration of CMGs’ Dynamics

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Abstract

ASTRO-G is a flexible satellite, which has challenging specifications for attitude control system (ACS) in order to achieve its space VLBI (Very Long Baseline Interferometry) mission, called VSOP (VLBI Space Observatory Programme)-2. VSOP-2 mission requires ASTRO-G to change its attitude angle for 3 deg in 15 s, and attitude angle error to be less than 0.002 deg after the maneuver, while VSOP-2 mission also requires ASTRO-G to equip a large deployable antenna. This antenna of 9 m diameter is for VLBI observation and, obviously, should be handled as flexible structure. For these reasons, ACS of Astro-G must have both high-speed and high-precision performance and robustness to uncertainty of flexible structures. In addition, high-speed maneuver mission also requires ASTRO-G to equip CMGs (Control Momentum Gyros), which have complex mechanism, and therefore need to be studied.

In this paper, we studied about ASTRO-G’s ACS with 2 DOF (Degree Of Freedom) control, consists of robust feedback control and reference with MNME (Modified Nil-Mode-Exciting) profiler, which is based on input shaping and NME profiler. We also studied how to use the CMGs as feedback actuator. The designed 2 DOF control were discussed through numerical simulations.

Introduction

A large and flexible satellite “ASTRO-G”, which will be launched in 2012, has a mission of radio astronomical observatory called Space-VLBI. For this radio astronomical observatory, 8 m diameter large deployable antenna, which obviously should be treated as flexible structure, will be equipped in ASTRO-G. Additionally, Space-VLBI mission needs ASTRO-G to observe two celestial objects alternately in one minute cycle. In this alternate observation, it is needed to direct antennas towards two objects: target celestial objects and reference celestial objects called Quasar. The observation durations need to be 15 sec; therefore, antenna re-orientation between target and reference celestial objects should be done in 15 sec. ASTRO-G is considered to realize this antenna re-orientation by attitude maneuvering of whole body. In Addition, when observing target or reference celestial object, error angle of antenna direc-
tion is needed to be less than 0.005 deg\(^1\). Thus, high precision attitude control is needed.

For high speed attitude maneuver, ASTRO-G should equip Control Momentum Gyros or CMGs, which can generate huge torque. CMGs, however, have a complex mechanism to generate torque. Therefore, whether ACS of large and flexible satellite can be designed enough to satisfy high-speed and high precision using CMGs should be studied.

For these reasons, we studied both ACS designing and CMGs control law for ASTRO-G. First, CMGs and their control law are described in sec 2. Second, a simple law for controlling CMGs are proposed in sec 3. Third, ACS designing are described in sec 4. Finally, thorough numerical simulations, designed ACS and proposed control law of CMGs are studied in sec 5.

2 Control law of CMGs

2.1 About CMG

CMG is an actuator which can generate huge torque, and used for precise attitude control of large spacecraft like space stations, or for high speed attitude maneuvering of satellites. Figure 1 shows an overview of a CMG\(^1\).

The principle of operation of a CMG is as follows: CMG has a rotating rotor in constant angular rate, which are supported by a gimbal, as shown in fig 1. By rotating the rotating rotor on gimbal axis, CMGs generate gyro effect torque

\[ T = \omega \times H, \]

where, \( T, \omega, H \) are generated torque [Nm], angular rate of the gimbal [rad/s], and angular momentum of the rotor [Nms], respectively.

\(^1\) This is an example of current study

Because torque generated by CMGs is given as cross product as eq. 1, the direction of the generated torque vector changes as gimbal rotates. Therefore, to generate desired torque, control law of CMGs should be studied.

2.2 Mission demand and actuator configuration of ASTRO-G

ASTRO-G will have its antenna’s radio wave axis parallel to z-axis of the body coordinate, and it is needed to direct antenna’s axis towards two celestial objects alternately. Because the rotation on antenna axis doesn’t affect the observation, there is no need for maneuvering on z-axis; therefore, all of 4 CMGs will be set to have its gimbal axis parallel to the z-axis\(^2\). The 4 CMGs, hereby, cannot generate torque on z-axis; however, the distance to the singular point can be set to be far during maneuvering on x- or y-axis. In addition, for high-precision attitude control, ASTRO-G will have skew configured 4 reaction wheels (RWs).

2.3 General Control law of CMGs

In the past, general control law of the CMGs was based on SR-inverse\(^2\) to calculate inverse kinematics of the CMGs\(^3\), whose initial state is pyramid arrangement as shown in fig. 2. However, in the case of ASTRO-G, all 4 CMGs will have its gimbal axis parallel to z-axis, and the initial state is not a pyramid type. Therefore, ASTRO-G have singularity that CMGs cannot generate z-axis torque. In addition, it is said that ASTRO-G has to have the antenna’s direction error to be less than 0.005 deg during observation, which is considered to be too accurate. SR-inverse method can avoid the singular point; however, this singularity avoidance is considered to be on the sacrifice of

\(^2\) Actuator configuration of the ASTRO-G presented in this paper is an example of current study.
the attitude accuracy near the singular point. Therefore, it is needed to study whether inverse kinematics calculation using SR-inverse is applicable for ASTRO-G or not.

2.4 An example of current strategy for ASTRO-G

In the current strategy of ASTRO-G, a rest-to-rest maneuver profile called Nil-Mode-Exciting (NME) profiler[4] is considered to be feed-forward reference of the gimbal angles. Figure 3 shows a control block diagram of the current strategy. Figure 3 shows that, in the current strategy, CMGs are not used for feedback actuator. Thus, current strategy has following features:

- less computational cost,
- ability of fast maneuvering without exciting any flexible modes if the modeling identification has well accuracy, and
- possibility of torque saturation of the RWs if identification of inertia matrix had poor accuracy.

For these features, current strategy needs model identification of good accuracy. In other words, current strategy is relatively poor robustness against modeling error, because it is mainly based on feed-forward control. To realize high-precision attitude maneuvering with feed-forward based attitude control law mentioned above, current strategy needs to do attitude maneuvering called “reference maneuvering” before the real VLBI observation mission begins.

However, to let the observation period longer is, of course, an inevitable demand. This can be done by decreasing the number of times of the reference maneuver; and the times of the reference maneuver can be decreased by designing feedback control which has robust to modeling error. Therefore, in the next section, control law of CMGs as feedback actuator is studied.

3 Proposed CMGs Control Law

3.1 Problems about the CMGs Control Law

Proposed CMGs control law is feedback based control law, in which gimbal angle reference is made by the attitude angle error. SR-inverse law mentioned in sec. 2.3, however, needs calculation of inverse matrix and therefore needs calculation costs. In addition, SR-inverse based CMGs control law sacrifice the attitude angle accuracy near the singular point. Because of these reasons, CMGs control law is desirable to be simple.

The reason why SR-inverse is used generally for CMGs control law is because of the existence of singular points in inverse kinematics. Specifically, a translation matrix from angular rate vector of the gimbal to output torque vector can be not full-rank matrix, and this corresponds to the singular points. Therefore, to avoid this singularity, more simple way is proposed. Here, following features are noted.

- 4 CMGs will be equipped, all of whose gimbal axis are parallel to the z-axis on body coordinate.
- VLBI observation needs high-speed attitude maneuvering on arbitrary axis in only x-y plane.
- Beside the CMGs, 4 RWs will be equipped. High-precision attitude control can be done with RWs.

3.2 Simplification of CMGs control law by adding a constraint

The proposed control law of CMGs is based on two pairs of CMGs. A pair of CMGs are constrained to move in line symmetry, and generate one torque vector. By constraining a pair of CMGs to move in line symmetry, inverse kinematics which needs singularity avoidance by SR-inverse can be simplified to scalar multiplication. Figure 4 shows an overview of proposed method.

In fig. 4, a pair of CMGs has a initial condition to deny
each other’s angular momentum. As the pair of CMGs moves in line symmetry on x axis as shown in fig. 4, angular momentum of y-axis direction is denied on each other’s all the time. For torque is equal to differentiation of the angular momentum, torque generated by CMGs in fig. 4 has only x-axis element. Here, the number of the parameter used in the pair of CMGs is one, and that of output is also one, which means norm of the torque. Therefore, inverse kinematics is done by scalar multiplication, which is simple and has no singularity.

3.3 CMG configuration for torque vector to be linear independent

Because the number of torque vector generated by CMGs discussed in foregoing section is one, it is needed to have 2 pairs of CMGs for generating arbitrary torque in x-y plane. In addition, these torque vectors should have linear independent in x-y plane. Thus, a initial configuration of the CMGs can be shown as in fig. 5. In fig. 5, CMGs have a number from 1 to 4.

As discussed in the foregoing section, a pair of CMGs generates one torque vector. In fig. 5, CMG1 and CMG3, and CMG2 and CMG4 are the pair of CMGs to move in line symmetry. In initial configuration, pairs of CMGs have to turn to angle $\theta$ deg from y-axis. Here, $\theta$ is a designed parameter for control system to be linear independent in x-y plane, and $\theta = 0$ means linear dependent.

Therefore, if parameter $\theta$ is relatively large value, gimbal reference becomes stable when maneuvering axis was set to x-axis. However, the maximum angular moment to give for the body decrease in proportion to $\cos \theta$. Thus, the parameter $\theta$ should be determined in consideration of the trade-off between the maximum angular moment to give for the body and the stability of the gimbal reference.

3.4 Torque distribution law

The CMGs usage in ASTRO-G can be general classified into following 3 classes by the magnitude of torque demand.

1. CMGs are used only for feed-forward actuator. In this case, 3 axes attitude error should be suppressed by RWs.
2. CMGs are used as feedback actuator.
   (a) Feedback torque parallel to the attitude axis is distributed for CMGs, and torque perpendicular to the attitude axis for RWs.
   (b) All the feedback torque in x-y plane are distributed to CMGs.

In case 1, because CMGs are used for feed-forward use only, RWs are used as feedback actuator in 3-axes. In case 2-(a), attitude error parallel to the maneuvering axis can be suppressed by CMGs. Therefore, even if the modeling identification of the diagonal element of inertia matrix is relatively less accurate, attitude error can be suppressed via using CMGs, however, torque perpendicular to the maneuvering axis should have suppressed by only RWs. In case 2-(b), all the torque demand in x-y plane was distributed for CMGs.

To design CMGs control system, saturation of the RWs should be studied. However, considering about the interference between axes, this paper dealt with case 2-(b). As a result, the block diagram of the designed 2 DOF control was shown as fig 6.

4 Attitude controller designing

4.1 $H_\infty$ feedback controller

In this paper, $H_\infty$ control was used for attitude controller. To design controller, first, plant was linearized by
Dynamics
Gimbal
Controller
RW
Saturation
Gimbal
Driving Law
Feedback
Controller
Feedforward
Controller

Fig.6 Designed 2 DOF control system with CMG control law

Fig.7 Singular values of nominal plant, residue modes and weighting function

taking CMGs dynamics away. Second, bounded model was converted to unbounded model, and third, truncation was done. Finally, $H_\infty$ controller was designed by hinfdmi command of MATLAB using truncated model. Figure 7 shows singular values of the truncated model, residual modes by truncation, and one of the weighting function used in $H_\infty$ designing. In addition, fig. 8 shows the analysis result of the controller.

4.2 Feed-forward reference

Feed-forward reference used here was method already proposed by us[5]. This reference is made by convolution of NME profiler and Input Shaping.

5 Numerical Simulations

In this section, designed controller, control law of CMGs, and torque distribution law are studied through numerical simulations. The numerical simulation model consists of dynamics of rigid mode, flexible mode and CMGs. The reference inputs for dynamics are gimbal angle of the CMGs and output torque of the RWs. As one of study example, RWs configurations is as follows: 4 skewed RWs, each RW can output 0.5 Nm torque.

Antenna gain loss, which is calculated from attitude angle error and state variables of the flexible structures, was used for the judgment whether ACS has been converged or not. Antenna gain loss is, literally, gain loss of the antenna for observation, and convergence of the ACS is shown as the antenna gain loss to be less than 0.02 dB. The period granted for the attitude maneuver was considered to be 15 sec.

Figure 9 shows numerical simulation results of the proposed CMGs control law, of the SR-inverse law, and, for comparison, of the linearized model which the CMG dynamics was eliminated. Figure 9 shows that SR-inverse law had slower convergence about 1 sec than that of proposed CMGs control law.

By comparing the simulation results of the linearized model and non-linear model with CMGs dynamics using proposed method, the proposed method has relatively
fast convergence. Qualitatively, the simulation model with CMGs dynamics has a delay correspond to control band of the CMGs control system. Therefore, to study this reversal phenomenon, transitions of the attitude angle of the same simulation results were shown in fig. 10.

In fig. 10, comparing linearized model and non-linearized model using proposed CMGs control law, the proposed method has slightly small overshoot rather than linearized model. This can be considered due to the change of the relationship between feed-forward controller and the plant. This change of the relationship is due to change of the inertia matrix of the plant by eliminating CMGs dynamics. Therefore, the overshoot of the linearized model can be suppressed by the good designing of the feed-forward controller.

The simulation result of the SR-inverse law has overshoot about 2.02 deg, which is 2 or 3 times of that of proposed method or linearized model. This can be considered to due to the sacrifice of the singularity avoidance of SR-inverse.

6 Conclusion

In this paper, law of the CMGs for ASTRO-G is studied. We proposed control law of the CMGs using specific property of the ASTRO-G’s mission, and actuator configuration of the ASTRO-G. Proposed control law of the CMGs needs only scalar calculation, and needs no complex calculation of the SR-inverse.

Proposed law was compared with SR-inverse, using numerical simulations. The simulation result with SR-inverse law has relatively large overshoot in attitude angle transition, and result in about 1 sec delay for convergence.

Proposed method was compared with linearized model which doesn’t have CMGs dynamics, and the results had oddness, that is the proposed method has early convergence. This was considered to due to the changes in inertia matrix when eliminating CMGs dynamics. Detail of this cause should be studied in future works.

Reference