Design of Attitude Control System for H2A-piggy Solar Sail Spacecraft

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Abstract

ISAS/JAXA is studying on the solar sail spacecraft for the future deep space explorations. As a part of the plan, we develop the probe whose weight is almost 10kg. The main purpose of this mission is to verify the photon propulsion of solar sail at the interplanetary space. This probe is planed to be launched by H2A as piggyback. The mission consists of three stages : (1) separation from H2A and injection into GTO, (2) delta-V by the deorbit motor, and (3) deployment of the membrane and verification of the photon propulsion. This paper discusses the attitude control system of the mission. The attitude motion of the probe in each stages is different. The alignment of the thrusters and the sensors are designed to be optimal through the all stages. Using this alignment, the attitude control laws are proposed. The feasibility of the mission is examined by numerical simulation.

H2A-piggy ソーラーセイル探査機の姿勢制御設計

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摘要

ISAS/JAXA ではソーラーセイル探査機に関する研究を行っている。その一環として、H2A ロケットによるピギーバック衛星として 10kg 程度の探査機を打ち上げ、惑星間空間においてソーラーセイルによる太陽光子推進を実証する計画を進めている。本研究では、このミッションにおける各フェーズで必要となる姿勢制御について検討した。このミッションのフェーズは、(1)H2A からの分離と GTO 軌道への投入、(2)固体モータによる惑星間軌道への投入、(3)ソーラーセイル膜の展開と光子推進の実証、の３つに大きく分けることができる。このそれぞれに対応した姿勢制御法を設計し、数値解析によって検証した。

1. Introduction

ISAS/JAXA is currently studying on the solar sail propulsion for future applications to deep space explorations. The solar sail is a means of propulsion utilizing the momentum of photons from the sun. In September 23, 2006, the small solar sail demonstration satellite (SSSAT) was launched by the 7th M-V rocket as the sub-payload. The main purpose of this satellite was electric power supply by the thin film solar cell. For the next step of the solar sail project, we are planning inter planetary space mission to demonstrate and evaluate the photon propulsion under the air drag free condition.

This demonstration spacecraft is launched by H2A rocket as a piggyback of the main satellite whose orbit is geostationary transfer orbit (GTO). In order to leave from the orbit to interplanetary space, this spacecraft has the deorbit motor. For the orbital transformation, this mission has three staged sequence: (1) separation from H2A and injection into GTO, (2) delta-V by the deorbit motor, and (3) deployment of the membrane and verification of the photon propulsion. The configuration of the spacecraft varies with stage, so the attitude control strategy needs to be designed for each stage.(See Fig.1)

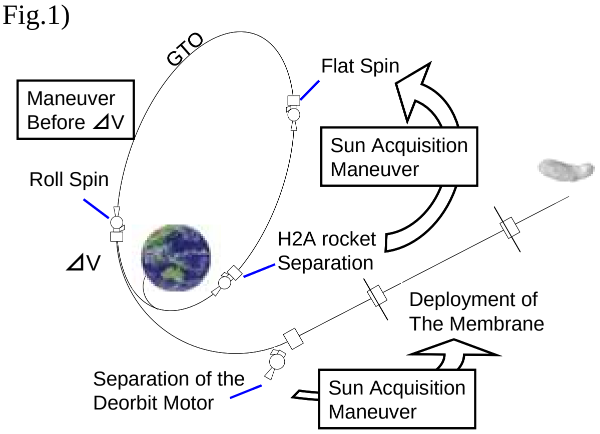

Fig.1: Mission Sequence

In this paper, the attitude control system for this spacecraft is designed.

First, the system alignment of the spacecraft and the attitude control device are introduced.

Next, we design the attitude control strategy for each stage. The attitude control system is consists of the spin rate control, active nutation control, and spin axis reorientation control. The mission sequence is designed using these control methods.

Finally, results of the analysis on the attitude control are shown. The spacecraft is spin stabilized type. To make the attitude stable, proper spin rate is estimated for each stage of the mission. The amount of the propellant consumed through the sequence is also estimated. The attitude control sequence must be designed within the limits of the amount of the propellant. Under this restriction, the feasibility of this mission is discussed.

2. System Configuration

2-1. Configuration

H2A-piggy solar sail spacecraft consists of the probe, the deorbit motor, and others such as ignition timing controller. (See Fig.2)

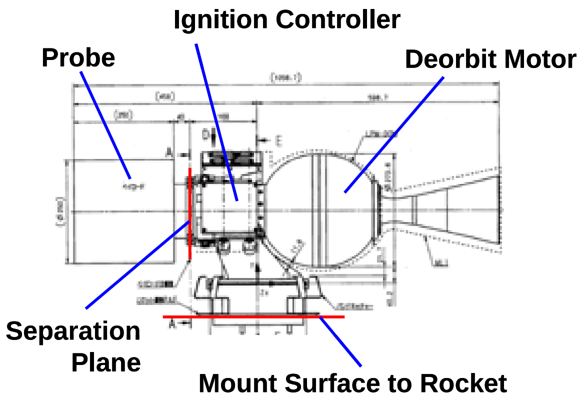

Fig.2: System Configuration

The probe is the modification of SSSAT. This has cylindrical body of 350mm diameter and 150mm height, and its weight is restricted under 10kg. The reaction control system and attitude sensors are mounted on the probe. The solar sail membrane is wound around the side surface of the probe, and deployed by the centrifugal force of the spinning probe.

The deorbit motor is originally developed for the penetrator of Lunar-A. After the injection of the probe into the interplanetary space, the motor and other parts are separated from the probe.

Fig.3 shows the coordinate axes used through this paper. The origin is set to the center of mass.

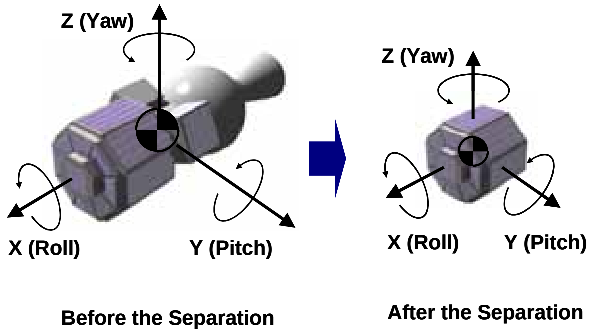

Fig.3 : The Coordinate Axes

Table.1 shows the estimation of the moment of inertia of the spacecraft. Before the separation, the spacecraft has the maximum principal axis of inertia on z-axis. After the separation, the probe has the maximum principal axis of inertia on x-axis.

Table1 : Moment of Inertia

	Before the separation [kg・mm^2]	After the separation [kg・mm^2]
Ixx	376659	124107
Iyy	2058304	78386
Izz	2103358	78386
Ixy	3336	10
Iyx	-1961	10
Ixz	2756	10

2-2. Reaction Control System

The probe has the gas-liquid equilibrium thruster, which uses LPG as propellant. This system can bring the propellant as liquid in the tank and eject the propellant as gas using the gas liquid equilibrium pressure to produces the thrust. This thruster system is simple and light weight [1].

For this spacecraft, “HFC-134a” is used as propellant. The thruster force is about 0.8N, and Isp is about 30sec.

This spacecraft has four thrusters for the reaction control system.

2-3. Attitude Sensors

For the attitude determination of the spacecraft, sun sensors and gyro sensor are used. In addition, we use the attitude determination method using RF-doppler measurements. In the method, the attitude of the spacecraft is determined by analyzing Doppler-frequency of RF signal from the probe received at ground station [2].

To monitor the sun direction continuously during spin period, we use two-dimensional position sensitive detector (2D-PSD, sun sensor). Two 2D-PSDs are mounted on the spacecraft. The sun direction is monitored for the spin around both X-axis and Z-axis. Fig.3 shows the alignment of 2D-PSD and thrusters.

Gyro sensor is mounted on the electrical circuit of CPU, and measures the spin rate around three axes.

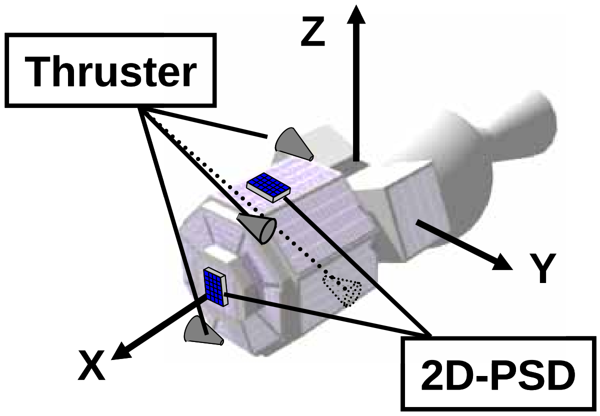

Fig.3: The alignment of thrusters and sensors

3. Attitude Control Strategy

For the spin solar sail satellite, we use mainly three attitude control logic as follow:

- Spin Rate Control
- Active Nutation Control (ANC)
- Spin Axis Reorientation

These control laws are effectively utilized for each stage.

3-1. Separation and Maneuver

The spacecraft is injected to GTO by H2A rocket, and then goes around that orbit several times. While the orbiting, z-axis of the spacecraft must be kept to face the sun so as to generate sufficient electricity. To keep such attitude stably, the spacecraft is put into a flat spin around z-axis.

In this mission, the following sequence is taken to make the spacecraft flat spin stabilization.

- Separation from H2A rocket
- Despin around x-axis
- Spin up around z-axis up to 0.1Hz(flat spin)
- Find the sun direction using 2D-PSD through the flat spin
- Reorientation of the spin axis towards the sun direction.

To find the sun direction easily during a spin period, one 2D-PSD is mounted on x-axis direction. To orient the spin axis towards the sun easily, another 2D-PSD mounted on z-axis direction.

3-2. Delta-V by the Deorbit Motor

After several periods on GTO, the spacecraft leaves the orbit to interplanetary space by the deorbit motor. Before the delta-V, precise attitude maneuver must be performed. This maneuver is performed in following sequence.

- Despin of the flat spin
- Spin up around x-axis up to 0.1Hz
- Rough reorientation of the spin axis to the deorbit direction
- Spin up around x-axis up to 1.0Hz
- Precise attitude maneuver to the deorbit direction
- Delta-V
- Separation of the deorbit motor

Spin axis reorientation on high spin rate of 1.0Hz needs much propellant. To reduce the large consumption of the propellant, the reorientation is performed in two stages as above.

To reorient the spin axis to the deorbit direction, we need another attitude determination method which is different from using sun sensor. For this reason, the attitude determination method using RF Doppler measurements is introduced, though the detail of the method is beyond the scope of this paper.

The deorbit motor keeps the thrust about 20sec for the injection of the probe to interplanetary space, and then the spacecraft transfer to ANC mode. After the nutation is removed, the probe is separated from the deorbit motor.

3-3. Deployment of Membrane

The probe reorients the spin axis to the sun before the deployment of the membrane. The reorientation is performed in two stages again. The following sequence is taken before the deployment of membrane.

- Spin around x-axis down to 0.1Hz
- Rough reorientation of the spin axis towards the sun
- Spin around x-axis up to 1.0Hz
- ANC
- Deployment of membrane

While the deployment of membrane, support control is performed in the same way of SSSAT. The detail of the control strategy is covered in [3].

4. Mission Analysis

4-1. Proper Spin Rate during the Flat Spin

The target spin rate of the spacecraft must be specified in terms of the stability of the attitude.

The target rate of the flat spin on first stage is specified to enable the spin axis towards the sun under the disturbance torque.

Here we estimate gravity-gradient torque, aerodynamic torque, and solar radiation torque based on the configuration of the spacecraft. The summation of disturbance torque act to the flat spinning spacecraft while a period of GTO is shown in Fig.4.

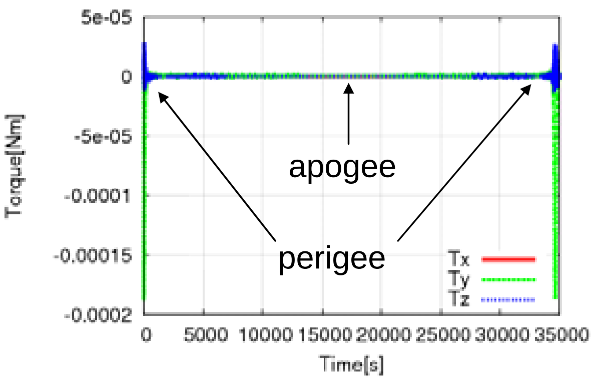

Fig.4 : Disturance torque while a period of GTO

In the GTO, the major disturbance torque is gravity-gradient torque except near the perigee, where the major disturbance torque is aerodynamic torque. The maximum torque is about $2.6e^{-4}$Nm. The integration of the torque for the orbital period becomes as follow:

$$\begin{cases} Nx = 6.8e^{-6}[Nm \cdot s] \\ Ny = 2.1e^{-2}[Nm \cdot s] \\ Nz = 1.9e^{-3}[Nm \cdot s] \end{cases}$$

This integrated torque is enough small to keep the direction of the flat spin of 0.1Hz. It follow that this spin rate is appropriate for the stable spin to keep z-axis face to the sun direction.

4-2. Proper Spin Rate before the Delta-V

The target rate of the roll spin on the second stage is specified to enable the spacecraft keep the target direction during the delta-V against the disturbance torque of the deorbit motor' s thrust.

Fig.5 shows the prospective time history of the thrust force of the deorbit motor.

If there is a misalignment between the thrust force vector and x-axis, large torque is generated about an axis orthogonal to the thrust vector. This disturbance torque would raise the nutation motion. However, it is known that if the changing rate of the thrust force is enough small compared to the spin rate, the declination of the angular momentum vector after the delta-V depends only on the initial thrust force.

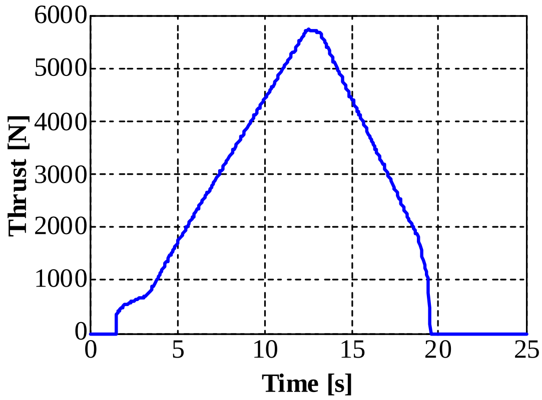

Fig.5 : Prospective thrust pattern of the deorbit motor

We simulate numerically the attitude motion of the spacecraft under the assumption that there is a offset of 4mm between the thrust force vector and x-axis.

Fig.6 shows time history of the nutation angle and the thrust force while the delta-V. The spin rate about x-axis is 1.0Hz. The nutation angle changes depend on disturbance torque generated by the misalignment.

When the spin rate is enough high compare to the changing rate of the thrust force, the disturbance torque is averaged during a spin period. As a result, the nutation angle converges.

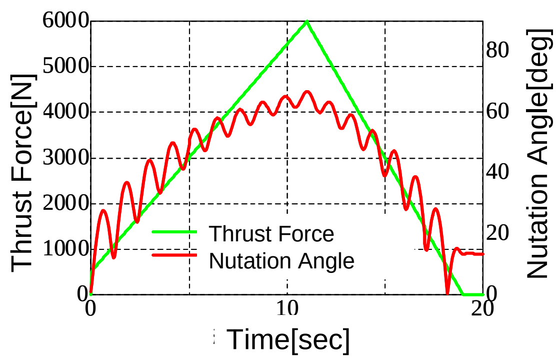

Fig.6 : Time History of Nutation Angle while Delta-V

Fig.7 shows the inclease of the velocity and the declination angle of the angular momentum vector after the delta-V for each spin rate.

If the spin rate is lower than 0.8Hz, the efficiency of the delta-V is drop significantly. For such low spin rate, the nutation motion diverges and the spacecraft turns over.

In conclusion, the x-axis spin should be upped to not less than 1.0Hz just before the delta-V.

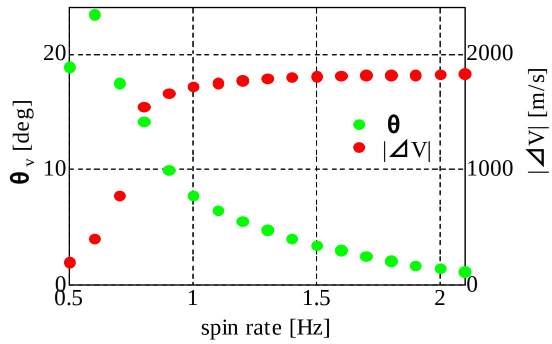

Fig.7 : The efficiency of the ⊿V for each spin rate

4-3. Propellant Analysis

The amount of propellant is restricted under 300[g] by the design condition of the spacecraft. We estimate the amount of the propellant consumed in each attitude control laws, and design the attitude control sequence properly.

The required propellant in spin up/down is calculated as follow:

$$M = \frac{I\Delta\omega}{l \cdot Isp \cdot g} \qquad (1)$$

where I is the moment of inertia about spin axis, l is the length of the moment arm.

On the other hand, the required propellant in reorientation is calculated as follow:

$$M = \frac{I\omega \cdot \Delta\theta}{l \cdot Isp \cdot g} \qquad (2)$$

where $\Delta\theta$ is the amount of inclined angle of the angular momentum vector.

Table 2 shows the result of estimation based on the equation (1) and (2).

Table2 :Estimation of the required propellant

Control mode	Required Propellant	
	Spin up/down	Reori at 1.0Hz spin
Flat Spin	156.7[g/Hz]	4.48[g/deg]
Roll Spin	45.97[g/Hz]	2.00[g/deg]
Probe Spin	15.15[g/Hz]	0.66[g/deg]

Reorientation control requires much propellant in proportion to the spin rate. This denotes that the amount of consumed propellant is reduced in some cases via the spin rate control before the reorientation.As shown in chapter 3, the reorientation control is performed with the spin rate control to reduce the large consumption of the propellant.

To estimate the amount of required propellant through the sequence designed at chapter 3, we use also the numerical simulation. On the simulation, the spacecraft control the attitude in line with the designed sequence, and calculates the expected consumption of the propellant.

Fig.8 shows the result of time history of the amount of propellant consumption. In addition to the eventual amount of the propellant, extra propellant is required to keep the tank pressure. Consequently, the total amount of required propellant is 285g. This result denotes that the all mission sequence is feasible with the propellant stored in the tank. However, in case the reorientation control is performed without spin rate control, the total amount of required propellant may over 300g.

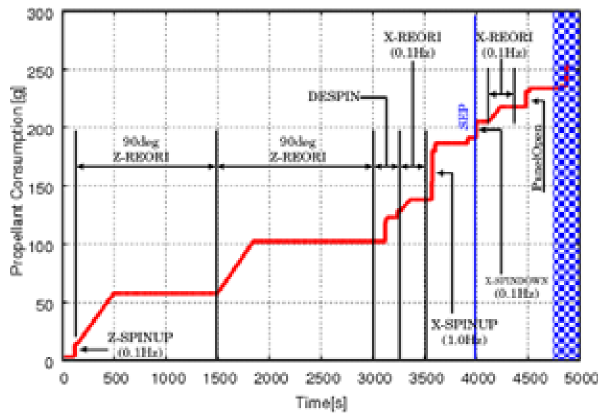

Fig.8: Consumption of the Propellant

5. Conclusion

This paper shows the design of attitude control system for H2A piggy solar sail spacecraft. The alignment of the attitude control and determination device is designed in line with the mission sequence of 3 stages. The attitude control laws are also designed, and the feasibility of the mission is examined by numerical simulations.

6. References

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