RW angular momentum analysis of Hayabusa 2 during Earth swing-by

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Key Words: Hayabusa2, Swing-by, attitude control, AOCS,

Abstract

Hayabusa2 had been launched on December 3, 2014 and successfully accomplished Earth swing-by 1 year after of the launch date. During swing-by, we observed that RW (Reaction Wheel) angular momentum has unexpectedly changed by the Earth disturbances. After swing-by operation, Hayabusa2 moves to cruising phase toward Ryugu, our destination. This paper shows overview of attitude operation during Earth swing-by as well as analysis result of RW angular momentum changing.

はやぶさ 2 スイングバイ時の RW 角運動量変化解析

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摘要

2014 年 12 月 3 日，種子島宇宙センターより打ち上げられた小惑星探査機「はやぶさ 2」は，初期運用フェーズ，EDVEGA フェーズを得て，一年後の 2015 年 12 月 3 日に地球に再接近，スイングバイを行い，小惑星「リュウグウ」への軌道変更と加速に成功した．そして，小惑星付近までイオンエンジン（IES）を用いて移動するトランスファフェーズへと移行した．本論文では，はやぶさ 2 のスイングバイ時及びその前後に地球が AOCS，特にリアクションホイール（RW）に与えた角運動量変化の影響に関して述べる．

Notation

$\vec{T}_{GG}$	Gravity-gradient torque
$\vec{\rho}$	Position vector from the mass center of the spacecraft to a point inside the spacecraft
$\vec{f}_G$	Gravity force
$\vec{R}_{CI}$ $\vec{r}$	Position vector from the Earth center to the mass center of the spacecraft
μ	Geocentric gravitational constant
ω_0	Orbital rotational speed
$\vec{b}_{OZ}$	Z axis unit vector from the Earth center to the mass center of the spacecraft
$\vec{T}_M$	Residual magnetic torque
$\vec{M}$	Residual magnetic moment
$\vec{B}_E$	Earth magnetic field vector
a^3H_0	Earth magnetic field dipole strength
$\vec{M}_E$	Earth dipole moment unit vector

1. Introduction

Hayabusa2, an asteroid explorer, had been launched from Tanegashima Space Center on December 3 2014, passed the critical operation phase and EDVEGA phase, after these phases, re-approached to the Earth just one year after from the launch date for acceleration by the Earth swing by, and changed the orbit to Ryugu, the asteroid of our destination. Hayabusa 2 is now in the transfer phase and trying to get required velocity by Ion Engine System (IES). In this paper, Hayabusa 2 Attitude and Orbit Control System (AOCS) overview is described at first, the effect in Hayabusa 2 AOCS during the Earth swing by, especially the effect in the Reaction Wheels (RW) is described, at last, the discussion about this effect to Hayabusa 2 and other spacecraft which IES is mounted on.

2. The overview of Hayabusa 2 AOCS

2.1. Frame

Some frames are defined in Hayabusa2, but the body fixed frame is used in this paper because attitude dynamics is mainly described. This frame's origin is the mass center, X axis is the direction from the origin to the panel which IES is mounted on, Z axis is the direction from the origin to high-gain antennas, and Y axis is the last direction which is determined from right-hand frame, X and Z axis. The body fixed frame is shown in Fig.1.

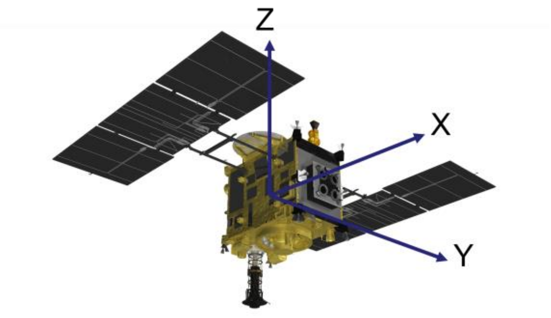

Fig.1 Hayabusa 2 body fixed frame

2.2. AOCS hardware [1]

In this section, main components in Hayabusa 2 AOCS is described. AOCS components are mainly divided actuators and sensors. These components are shown in Table.1 and Table.2 as well as the mounted positions of some components are shown in Fig.2. The small angle attitude maneuvers are executed by RWs, but the large angle attitude maneuvers, which exceed 10 degrees, are executed by RCSs. In addition, RCS is used for unloading of RWs.

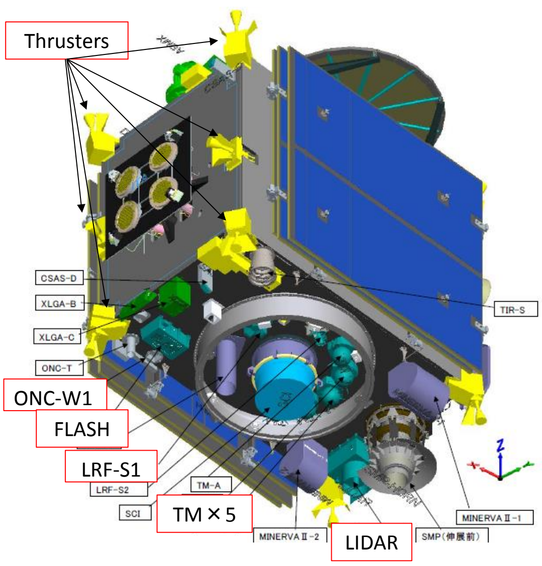

Fig.2 Sensors and actuators mounted positions

Table.1 AOCS sensors

	Function
CSAS	Coarse Sun Aspect Sensor: detects sun direction and is used attitude determination and acquisition of the sun direction during safe hold mode
STT	STar Tracker: detects the star directions and is used for attitude determination
IRU	Inertial Reference Unit: detects the rotational speeds and is used for attitude determination
ACM	ACcelerometer: detects the accelerations and is used the position estimation.
ONC	Optical Navigation Camera: is used in the mission phase and estimates the relative position to the asteroid
LIDAR	LIght Detection And Ranging: measures the distance from the spacecraft to the asteroid surface and measures the altitude
LRF	Laser Range Finder: measures the relative inclination of the asteroid local plane and the altitude
TM	Target Marker: is a marker for autonomous navigation during the final descent
FLA	FLAsh lamp: TM reflects the light for image measurement

Table.2 AOCS actuators

	Function
RCS	Reaction Control System: thrusters for attitude and orbit control
RW	Reaction Wheel: are used for attitude control and deployed 1 RW on X and Y axis and 2 RWs on Z axis

Table.3 Some control modes

Control mode	Concept
RCS 3 axis control mode	Controls 3 axis by STT and IRU navigation and RCS
Wheel 3 axis control mode (W3AX mode)	Controls 3 axis by STT and IRU navigation and 3 RWs
One RW control mode (OWC mode)	Control attitude by using RW on Z axis with biased rotation al speed

2.3. The Control modes

Hayabusa 2 main control modes are shown in Table.3. The attitude and orbit control is operated by the combination of these control modes in EDVEGA phase, Earth swing by phase, transfer phase, mission phase, and contingency case. W3AX mode and OWC mode are basically used in Hayabusa 2 mission.

Zero-momentum stabilization is used for the spacecraft attitude control in W3AX mode. Only one RW which is mounted on Z axis is used in OWC mode and other axis is controlled by sun radiation pressure.

3. AOCS operation result and analysis during the Earth swing by

In this chapter, AOCS operation during the Earth swing by and analysis of RW angular momentum changing and attitude dynamics are described.

During the Earth swing by, the attitude of the spacecraft main body indicated sun-oriented direction and controlled by W3AX mode as well as IES was turned off. Thus, the attitude was controlled by RWs and absorbing the effect of the disturbances not to change the attitude. Authors observed that RWs rotational speed were made a big change and the speed were larger than before and after swing by at that time. RWs change few rpm in a day, but the maximum changing number was about 600 rpm in a few hours during swing by. It means Hayabusa 2 was applied larger disturbances from the Earth and RWs controlled the larger angular momentum than usual.

In the following, what the main reason of these disturbances is described with the result of analysis.

At first, the flying orbit of Hayabusa 2 is shown in Fig.3. Hayabusa 2 moved from the arctic direction to the Antarctic direction. The distance from the Earth center to the spacecraft was about 9500 km and had about 20 minutes' shade time when the spacecraft re-approached the closest to the Earth.

The time history of changing of RWs' angular momentums are shown in Fig.4. These value means disturbances were absorbed by angular momentums to stabilize the spacecraft attitude and UTC 10:05 is the symmetric axis of the changing. This symmetric axis is plotted very close to the closest approach time to the Earth, and the relative distance between the spacecraft and the Earth causes these angular momentum changing.

In general, the gravity-gradient torque, the residual magnetic torque by the Earth magnetic field, the sun radiation pressure, and the atmospheric drag are considered as the reason of the disturbance [2]. However, from the study as it is mentioned before, the altitude of Hayabusa 2 was too high that the effect of the atmosphere drag to the spacecraft was very small as well as Hayabusa 2 was in the shade of the Earth and the effect of the sun radiation pressure was also very small. For these reason, it is estimated that the main reason was the gravity-gradient torque and the residual magnetic torque.

The gravity gradient torque was calculated from the following formula.

$$\vec{\mathbf{T}}_{GG} = \int_B \vec{\boldsymbol{\rho}} \times d\vec{\mathbf{f}}_G = \frac{3\mu}{R_{CI}^5}\vec{\mathbf{R}}_{CI} \times \mathbf{I}\cdot\vec{\mathbf{R}}_{CI} = 3\omega_0^2\,\vec{\mathbf{b}}_{Oz} \times \mathbf{I}\cdot\vec{\mathbf{b}}_{Oz}$$

The residual magnetic torque was calculated from the following formula.

$$\vec{\mathbf{T}}_M = \vec{\mathbf{M}} \times \vec{\mathbf{B}}_E$$

$$\vec{\mathbf{B}}_E = \frac{a^3 H_0}{r^3}\left\{3\left(\frac{\vec{\mathbf{r}}}{r}\cdot\vec{\mathbf{M}}_E\right)\frac{\vec{\mathbf{r}}}{r} - \vec{\mathbf{M}}_E\right\}$$

In this formula, the magnetic moment of the permanent magnets in IES was used as the residual magnetic moment M because it is the most dominant in Hayabusa 2, as well as the Earth magnetic field vector was calculated from IGRF model. The Earth magnetic field above altitude 3000m is shown in Fig. 5.

The analysis results are shown in Fig.6 and Fig.7. From these analysis, the largest gravity-gradient torque was applied to the X axis, and the large angular momentum changing of the residual magnetic torque were applied to Y and Z axis. These result match with qualitative understanding, which means Hayabusa 2 solar array panels are mounted on the Y panels and the Earth magnetic field vector was changed from plus to minus Z axis.

Fig.8 shows the total angular momentum of these 2 analysis, and this result matches very well with telemetry data. From this analysis, the changing of RWs' angular momentum during the Earth swing by was mainly caused by the gravity-gradient torque on X axis and the residual magnetic torque on Y and Z axis.

This analysis helps to understand the IES residual magnetic moment in orbit, and a spacecraft which orbit or fly by a planet which has high magnetic field such as the Earth or the Jupiter has a possibility that large disturbance may be applied to the spacecraft and the spacecraft may use much propellant to control its own attitude or much load may be applied to RWs. This analysis shows that this point should be considered carefully in AOCS design and operation.

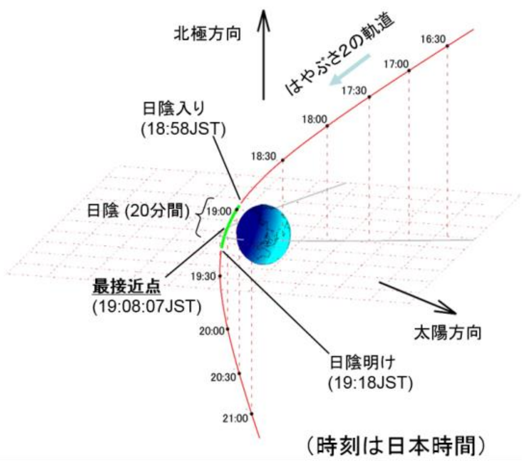

Fig.3 the Earth swing by orbit

Table.5 Analysis conditions

Conditions	Value
Start time (UTC)	09:06:47 Dec. 03. 2015
End time (UTC)	10:34:32 Dec. 03. 2015
Time step	2 [sec]
RW moment of inertia	0.0095 [kgm^2]
Earth's magnetic field model	IGRF
Residual magnetic moment	[100.4, 0.0, 0.0] [Am^2]

Table.6 Analysis result summary

Control		Value [Nms]	
X-axis Max	X-axis Min	2.8214	2.7296
Y-axis Max	Y-axis Min	2.8664	2.2391
Z-axis Max	Z-axis Min	2.7590	2.3438
Disturbances		Value [Nms]	
X-axis Max	X-axis Min	2.7879	2.7243
Y-axis Max	Y-axis Min	2.7949	2.1195
Z-axis Max	Z-axis Min	2.7667	2.3147

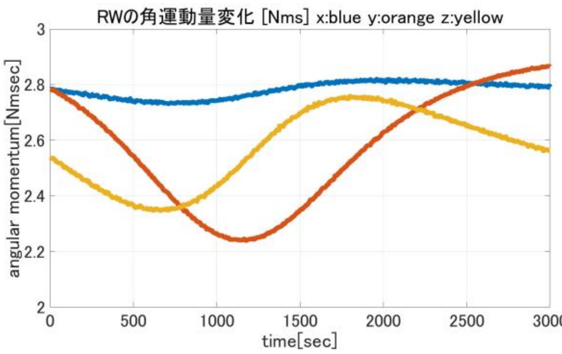

Fig.4 History of RW angular momentum (Telemetry data) (Blue: X axis, Orange: Y axis, Yellow: Z axis)

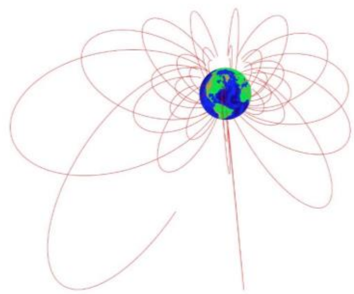

Fig.5 the Earth magnetic field when the closest approach (above 3000 km altitude)

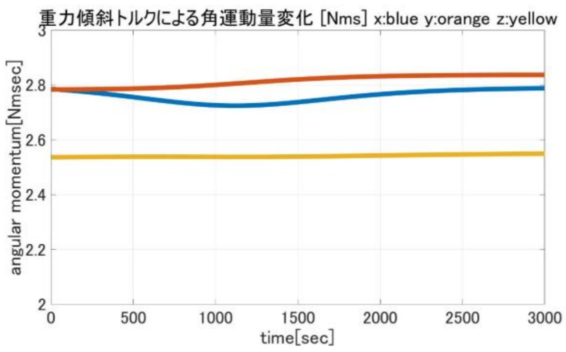

Fig.6　History of angular momentum which is calculated from the gravity-gradient torque (Analyzed data) (Blue: X axis, Orange: Y axis, Yellow: Z axis)

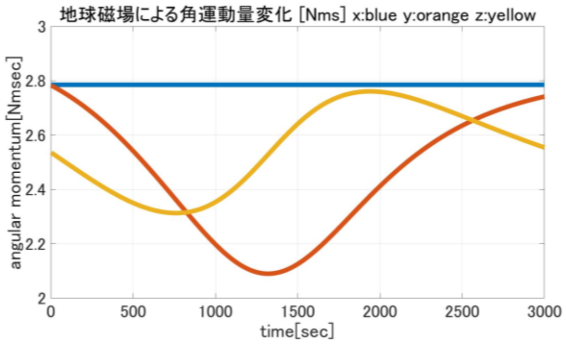

Fig.7　History of angular momentum which is calculated from the residual magnetic torque (Analyzed data) (Blue: X axis, Orange: Y axis, Yellow: Z axis)

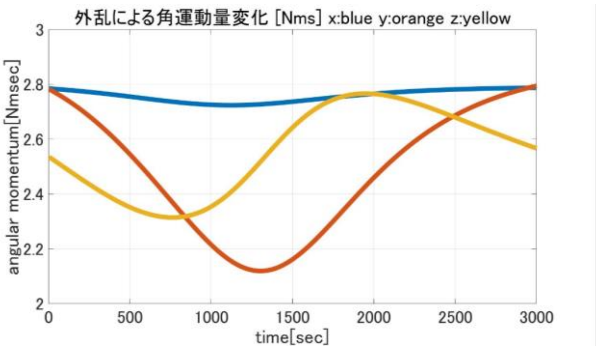

Fig.8　History of angular momentum which is calculated from the total disturbance torque (Analyzed data) (Blue: X axis, Orange: Y axis, Yellow: Z axis)

4.　Conclusion

Hayabusa 2 is operated safely by project team members and traveling to the asteroid Ryugu for arrival to the asteroid in 2018 summer. In this paper, as the latest topic of the operation, the analysis of the effect to AOCS during Earth swing by is described.

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