Reducing Accumulated Momentum by Independent SAP Control for DESTINY+ mission

Yusuke Ozawa[1], Hiroki Nakagawa[1], Seiji Yasuda[1] and Toshio Kamiya[1]
1. NEC, Space System Division

DESTINY+ which has been developed in ISAS/JAXA will be operated around the Earth and deep-space to demonstrate spiral raising and interplanetary transfer to Phaethon. In this mission, there are some disturbance torques caused by air drag, solar radiation pressure, and swirl torque of ion engine thrusters. To release the momentum accumulated in the reaction wheel, thruster unloading is operated basically, however, the fuel mass consumed by the operation has critical effect to spacecraft mass budget.

To reduce the fuel consumption, an unloading algorithm that utilize controllability of solar panels is planned to be applied for this mission. The proposed algorithm is to control the angles of two panels independently and change the center of radiation pressure or create swirl torque actively. In this paper, effectiveness of the proposed algorithm is demonstrated by numerical simulation with spacecraft configuration.

DESTINY+における SAP 独立駆動制御による蓄積外乱除去アルゴリズム

小澤祐亮 [1], 中川弘喜 [1]、保田誠司 [1]、神谷俊夫 [1]
1 . NEC, 宇宙システム事業部

DESTINY+は ISAS/JAXA によって開発中の深宇宙探査機である。本探査機は、地球周回の長楕円軌道に打ち上げられたのち、IES を稼働することで、軌道を徐々に上昇させるスパイラル軌道上昇をとり、地球圏を脱出する。惑星航行を経た後、小惑星 3200Phaethon の高速フライバイ観測を行う。

本ミッションでは、大気抵抗や太陽輻射圧、IES によるスワールトルクなどの外乱によって角運動量蓄積が長期間にわたって生じる。RW に蓄積された角運動量を放出するために、一般的にはスラスタによるアンローディングを実施するが、蓄積外乱量を放出するための推薬は探査機質量増加に大きく影響する。

本論文では、アンローディングによる推薬消費量を節約するために、２枚の太陽電池パネル(SAP)を独立的に駆動することによって、蓄積角運動量を低減させる極性へ太陽輻射圧トルクを能動的に作用させる手法を提案する。提案手法を DESTINY+特有のミッション制約や軌道を考慮して評価を行い、アンロードのための消費推薬量が低減されたことを定量的に示した。

1. Introduction

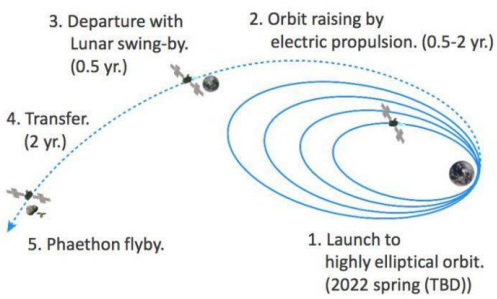
DESTINY+ (Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science) is one of the most challenging mission which has been developed in ISAS/JAXA. Its status is under development and it will be launched by Epsilon rocked in 2024.

The main mission purpose is to observe an asteroid 3200 Phaethon.[1].After launched by Epsilon Rocket, the spacecraft will be deployed into a highly elliptical earth orbit (altitude 230km×37000km). To escape the earth gravity field, the spacecraft will operate Ion Engine Subsystem (IES) and gradually raise the altitude. After escaping from the Earth, transferring to the Phaethon with IES [2]. Due to

the long term transferring around the Earth and interplanetary, the disturbance torques are accumulated massively.

The accumulated momentum is eliminated with the thruster (RCS unloading: RCS-UNL) and IES. IES can also remove the accumulated momentum by controlling the thrust direction (IES-UNL). To economize the fuel mass for RCS-UNL, We need the method which can unload the momentum without the fuel reducing.

Credit: JAXA/ISAS, Go Miyazaki (カシカガク) [3]



Credit: JAXA/ISAS [3]

Figure 1. DESTINY+ mission overview.

2. Proposed Method

To reduce the fuel mass for unloading, we utilize the environmental disturbance for unloading the accumulated momentum. Unloading torques with Solar Radiation Pressure (SRP) are generated by an unbalance of areas of Solar Array Panels (SAP) as showed in Figure 2. The upper side of schematic figure shows the idea of torque generation like windmill with tilting each side of panel for opposite polarity, and the bottom one shows the torque generation for two axis with actuating only one side of panel.

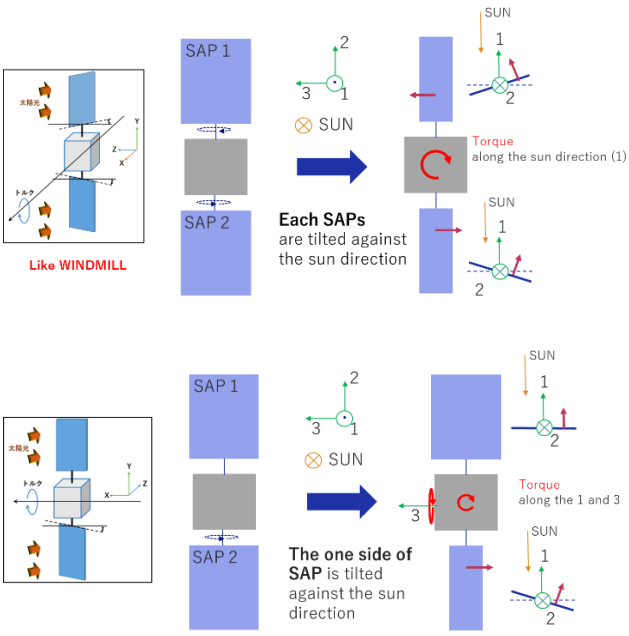


Figure 2. The scheme of SAP unloading.

3. Analysis

In this section, we evaluate the effectiveness of SAP-UNL. As a first step, the analysis without SAP-UNL is performed as a baseline. For the second step, the SAP-UNL are performed and calculate the effectiveness.

3.1. Analysis Condition: Mission Period

The mission duration of each operating phase are showed in Table 1. Sun distance are 0.98 AU for phase A, B and C, and 0.88 AU for D and E. Sun direction is considered as –X, -Z, +X side for phase B and D (IES acceleration attitude), and –Z side for phase A, C, E (Sun hold attitude).

Table 1. Mission duration of each operating phase

ID	Phase	Duration [day]
A	Check out phase	30
B	Spiral raising phase	470
C	Lunar swing-by Phase	282
D	Interplanetary (w IES)	100
E	Interplanetary (w/o IES)	1368
-	Total	2250

Table 2 shows the altitude for check out phase (A) and

spiral raising phase (B). As seen in the table, this mission will be started with the low perigee and the high apogee.

Around the Earth, there are some disturbance forces affect to the spacecraft. Aerodynamic torque that mainly affects between 100 to1000km, the gravity-gradient torque that mainly affects between 1000km to 30000km, and the magnetic disturbance torque that mainly affects between 1000km to 3000km, and the solar radiation torque that mainly affect from 30000km and more. For the disturbance model, these environmental torques and IES swirl torque are take into account.

Table 2 Altitude of spiral trajectory.

[day]	Perigee [km]	Apogee [km]
0~30	223	36,989
30~100	223	36,989
100~200	3,854	46,266
200~300	13,963	67,080
300~400	27,638	98,993
400~500	47,919	160,478

3.2. Analysis Condition: Spacecraft Configuration

The controllability of each unloading are constrained as show in Figure 3 due to the system design of DESTINY+.

IES-UNL and SAP-UNL cannot be used for unloading the momentum of X-axis and Y-axis respectively. IES is attached on +X panel (as shown in Figure 3) and the unloading torque can be generated only around Y/Z-axis. In the same way, the SAP-UNL can generate the torque around X/Z-axis.

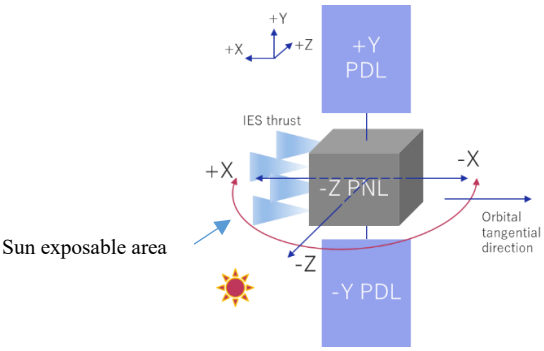


Figure 3 Constraints of system design

Table 3 Controllability of each unloading

	X	Y	Z
SAP-UNL	○	N/A	○
IES-UNL	N/A	○	○
RCS-UNL	○	○	○

○…Unloadable, N/A…Not unloadable

3.3. Analysis without SAP-UNL

At first, the disturbance are analyzed for all mission life. The result of disturbance analysis are shown in Table 5. The black values of each sell are accumulated momentum without IES-UNL/SAP-UNL. The slashed value are the reduced value by IES-UNL. As shown in Figure 8, the average torques for one orbit of IES-UNL (blue-dashed line) torque are greater than the total of other disturbance.

From these results, the accumulated momentum for Y/Z axis on spiral phase can be reduced by IES-UNL. The Accumulated momentum without SAP-UNL is shown in the left side of Figure 9. The mass of fuel for RCS-UNL is 3.57kg.

3.4. Analysis with SAP-UNL

From the result of without SAP-UNL, there are a great amount of accumulated momentum for X-axis. It indicated that SAP-UNL with X-axis makes a profit of reducing the fuel mass. In this SAP-UNL analysis, SAP-UNL is considered for the two cases; Case 1: with IES operating case; spiral raising (B) and interplanetary (D), and Case 2: without IES operating case, lunar swing-by (C) and interplanetary (E). From this analysis, the reduced accumulated momentum is shown in Table 5 as red value. The total accumulated value for X-axis is reduced from 1113Nms to 408Nms. Its value for fuel mass is 1.84kg.

3.4.1. Case 1: For phase (B) and (D) (with IES case)

In this phase, the sun direction with regard to the body frame move around –X/-Z/+X, because the –X-axis points to velocity vector to accelerate the spacecraft with IES.

From this condition, to reduce the accumulated momentum for X-axis, SAP-UNL can be operated as shown in Figure 4. The left-side is the case of -Z sun-direction, and the right-side is the case of +X sun-direction. Figure 5 is generated torque with each sun direction. From this analysis, SAP-UNL can almost reduce the accumulated momentum after 300 days. The value of momentum after reduced with SAP-UNL is shown as red figure in the row No.2,3 of Table 5.

3.4.2. Case 2: For phase (C) and (E) (without IES case)

In this phase, IES is not operated. The spacecraft attitude is the sun-hold attitude that –Z points to the sun direction.

To reduce the X-axis momentum in this situation, SAP-UNL should be operated as showed in Figure 6. When the sun direction is in the –Z direction, the one side of panel must be tilted to reduce X-axis moment. The polarity of tilt direction is decided with the current polarity of Z-axis momentum to reduce both the Z and X-axis momentum. Figure 7 is generated torque with each sun direction. The value of momentum after reduced with SAP-UNL is shown as red figure in the row No.4 of Table 5.

Table 4 Disturbance and SAP-UNL momentum (for case 1)

Day after launch [day]	Disturbance [Nms/day]	SAP-UNL [Nms/day]
30	~±5.08	-0.983~+0.855
100	~±2.06	-0.983~+0.855
200	~±1.18	-0.983~+0.855
300	~±0.94	-0.983~+0.855
400	~±0.88	-0.983~+0.855
500	~±0.86	-0.983~+0.855

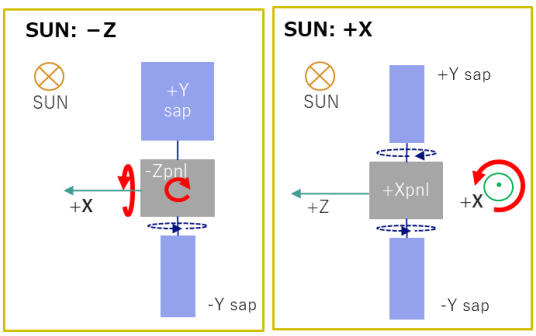


Figure 4 Unloading torque for case 1

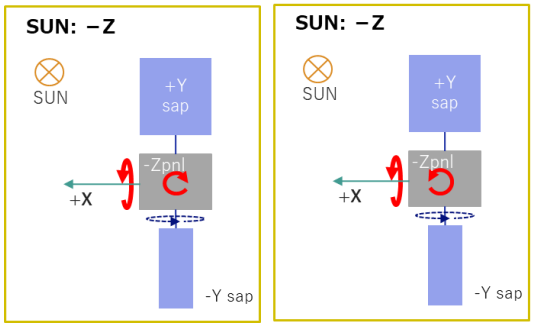


Figure 6 Unloading torque for case 2

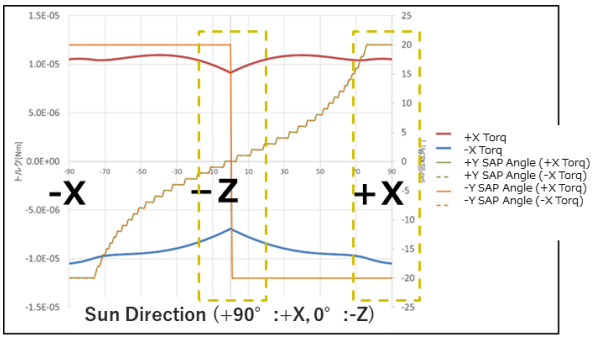


Figure 5 Generated unloading torque with each sun-direction. (for case 1)

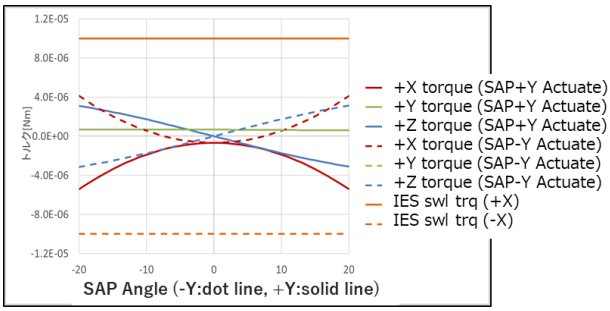


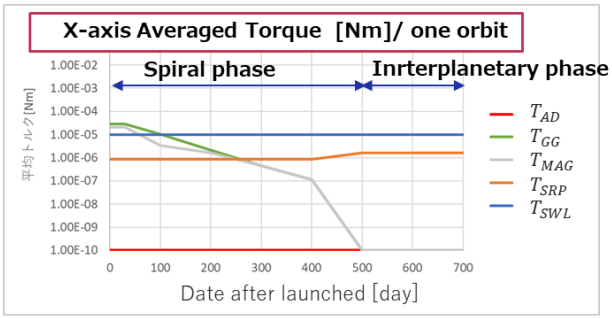
Figure 7 Generated unloading torque with each sap angle. (for case 2)

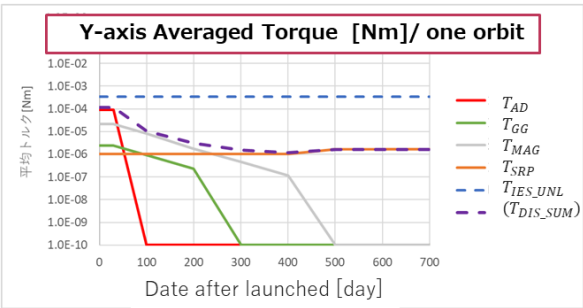
Table 5 The accumulated momentum for each phase

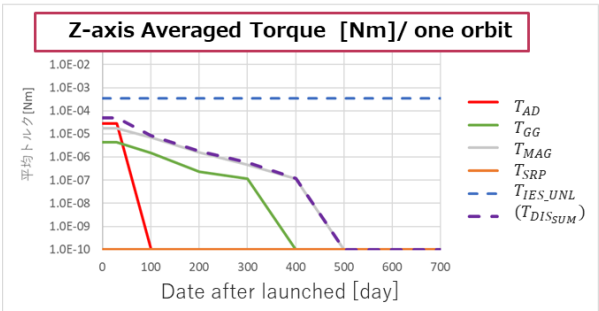
No.	Phase	IES	day	Accumulate momentum[Nms]															Total [Nms]		
				T_AD			T_GG			T_MAG			T_SRP			T_SWL					
				X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1	Spiral	OFF	~30	0	240	72	74	6	12	53	56	46	2	3	0	0	0	0	129	305	130
2		ON	30~500	0	~~160~~ 0	~~48~~ 0	185 **61**	~~15~~ 2	~~25~~ 2	106 **35**	~~134~~ 13	~~113~~ 10	34 **11**	~~41~~ 1	~~0~~ 0	325 **107**	~~0~~ 0	~~0~~ 0	650 **214**	~~350~~ 16	~~186~~ 12
Spiral phase subtotal[Nms]				0	240	72	259 **135**	8	14	159 **88**	69	56	36 **13**	4	0	325 **107**	0	0	779 **343**	321	142
3	Interplanetary	ON	100	0	0	0	0	0	0	0	0	0	14 **9**	14	0	86 **56**	0	0	100 **65**	14	0
4		OFF	1650	0	0	0	0	0	0	0	0	0	234 **0**	234	0	0	0	0	234 **0**	234	0
Interplanetary phase subtotal[Nms]				0	0	0	0	0	0	0	0	0	248 **9**	234	0	86 **56**	0	0	334 **65**	234	0
Accumulated momentum total[Nms]				0	240	72	259 **135**	8	14	159 **88**	69	56	284 **22**	238	0	411 **164**	0	0	1113 **408**	555	142

(T_AD: Aerodynamic torque, T_GG: gravitational torque, T_MAG: magnetic torque, T_SRP: Solar radiation torque , T_SWL: IES swirl torque)

The values of each cell are an accumulated momentum. The number of slashed cell is reduced value by IES-UNL, and the red number is reduced value by SAP-UNL.







- Y/Z axis torques:
  - The sum of disturbance torques are smaller than the IES-UNL torque
  - Y/X axis accumulated momentum can be eliminated by IES-UNL
- X axis torque:
  - cannot be eliminated by IES-UNL because of DESTINY+ configuration

Figure 8 The averaged disturbance torque for one orbit

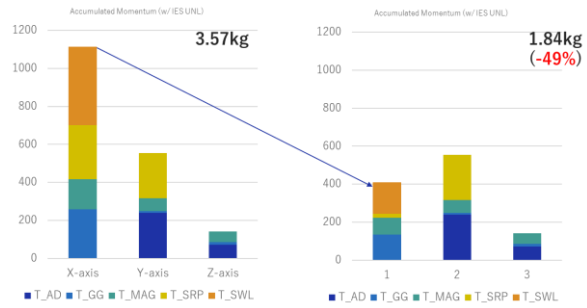


Figure 9 The total accumulated momentum without SAP-UNL (left-side), with SAP-UNL (right-side).

4. Conclusion

By using SAP-UNL, the accumulated momentum for X-axis is drastically reduced (-48%).

For the future work, we should evaluate the simulation on finer time with combined IES/SAP/RCS unloading logics to calculate more precise data.

In the 0-30days after launch, after critical phase, there are a lot of momentum are accumulated because of aero-dynamics. To earn more unloading torque around the perigee for initial phase, SAP-UNL with aero-dynamics is the one of the effective methods.

Reference

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[2] SARLI, Bruno Victorino, et al. DESTINY+ trajectory design to (3200) Phaethon. The Journal of the Astronautical Sciences, 2018, 65.1: 82-110.

[3] DESTINY+ – Demonstration and Experiment of Space Technology for INterplanetary voYage, Phaethon fLyby and dUst Science (jaxa.jp)