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# Engineering Notes

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## Mitigation Method of Spacecraft Momentum by Solar Radiation Pressure

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### I. Introduction

THE multipurpose geostationary satellite, COMS (Communication, Ocean, and Meteorological Satellite), was developed for communication, ocean, and meteorological missions in Korea. This spacecraft has a single solar array, due to payload requirements for ocean and meteorology missions. GOES (Geostationary Operation Environmental Satellite) for meteorology imaging is also a satellite with a single solar array. An on-station satellite is influenced by disturbance torques. Disturbance torque includes aerodynamic torques, magnetic torques, torques due to solar radiation pressure, and gravity-gradient torques. Among disturbance torques, aerodynamic torques, magnetic torques, and gravity-gradient torques are relatively small compared with torques due to solar radiation pressure in geostationary satellites such as COMS. Because of configuration, an asymmetric satellite has a problem with momentum accumulation due to solar radiation pressure when compared with a symmetric satellite [1–3]. The accumulated wheel momentum increases during the operation of a single-solar-array satellite. Thus, periodic momentum dumping is required to maintain a level of momentum in the reaction wheels of satellite. GOES deploys a solar sail boom to reduce the momentum increase due to its asymmetric body shape. A solar sail boom plays the role of equivalent weight. However, if there is insufficient space for establishing a solar sail boom, this method cannot be used, because a deployment equipment structure and a solar sail boom cannot be installed on the opposite side of the solar array [4]. In this Note, methods of reducing momentum dumping are studied. The proposed methods use solar radiation pressure and mass-center portion management. These methods contribute to resolving the momentum dumping problem in single-solar-array satellites, which lack sufficient space to establish a solar sail boom.

### II. Momentum Dumping Method Using Solar Radiation Pressure

In this section, the methods for reducing accumulated momentum using solar radiation pressure are introduced.

#### A. Relocation of Mass Center of Spacecraft by Propellant Blowdown

The first method is to change the mass center of the spacecraft by mounting a blowdown-type propellant tank. The mass center of the spacecraft is moved to the propellant blowdown direction as propellant is consumed during its lifetime. This movement of the spacecraft mass center can be used for reducing the momentum accumulation. The effectiveness of this method is increased as the satellite consumes the propellant because of the increment of its moment arm. As the propellant is consumed, the mass center of COMS will be moved to the $+Z$ axis, because the propellant tank is attached to the $-Z$ plate. In the case of COMS, if the propellant tank is located at the $-Y$ side and the blowdown direction is the $-Y$ axis, which is the opposite direction of the solar array, the mass center will then be moved in the $+Y$ direction, according to the consumption of propellant. If the mass center moves in the direction of the solar array, the length of the solar array moment arm is decreased and the effect of momentum dumping is improved.

#### B. Orthogonal Positioning of the Solar Array

If the battery is fully charged, the electric energy that is generated by the solar array will be directly used for the spacecraft bus, and excessive power will be shunted. Hence, when the battery is fully charged, the solar array orientation may not be constrained toward the sun all the time. If the direction of the solar array is orthogonal to the sun direction, solar radiation disturbance torque is minimized. The satellite should perform battery reconditioning, which improves battery performance before eclipse season. Using this method, the battery can be reconditioned. This method is attractive because it reduces the source of disturbance torque, but it is dependent on the battery's capacity and the satellite's power consumption. If the consumption of electrical energy is reduced, the time span for orthogonal positioning of the solar array can be extended.

#### C. Solar Array Offset Angle Control

Another method to reduce the momentum accumulation is to use the solar array offset angle. The geostationary orbit satellite points the solar array toward the sun to maximize power generation. The accumulated momentum is proportional to the area of the solar array and the length of the moment arm. As the solar array offset angle from the sun is increased, the momentum accumulation and power generation are decreased. For applying the solar array offset angle, it is necessary to analyze the electric power system of the satellite. If the offset angle is applied and the required electric power is maintained, the accumulated momentum can be reduced. The generated electric power varies according to the satellite's lifetime and the season, and so the offset angle is applied differently. Though applying the offset angle is a complicated method, if a careful analysis is accomplished, this method can save propellant for the momentum dumping process.

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Table 1 Mass center of the COMS satellite

| | Before relocation of propellant tank (current) | | After relocation of propellant tank (suggested) | |
|---|---|---|---|---|
| | Beginning of life | End of life | Beginning of life | End of life |
| Mass, kg | 1554 | 1239 | 1554 | 1239 |
| $X_{c.g.}$, m | −0.003 | −0.003 | −0.003 | −0.003 |
| $Y_{c.g.}$, m | 0.100 | 0.125 | 0.277 | 0.434 |
| $Z_{c.g.}$, m | 1.260 | 1.417 | 1.260 | 1.285 |

Table 2 COMS power property

| | Daily power yield | Available offset angle | Daily power requirement |
|---|---|---|---|
| Beginning of life | 2946.9 W | 38.78 deg | 2297.0 W |
| End of life | 2650.2 W | 29.92 deg | 2297.0 W |

Table 3 Maximum offset angle

| Operation year | Offset angle, deg |
|---|---|
| 2009 | 38.35 |
| 2010 | 37.46 |
| 2011 | 36.57 |
| 2012 | 35.68 |
| 2013 | 34.80 |
| 2014 | 33.91 |
| 2015 | 33.02 |
| 2016 | 32.14 |
| 2017 | 31.25 |
| 2018 | 30.36 |

## III. Simulation Analysis of Momentum Dumping

In this section, the proposed method is analyzed via a simulation using COMS as the example. Equation (1) represents the force of solar radiation pressure induced in a solar array [5]:

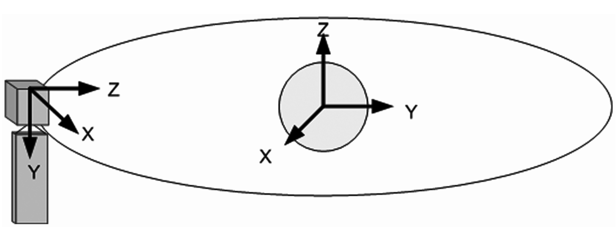


Fig. 1 Definition of coordinates.

$$\boldsymbol{F}_{\mathbf{sp}} = -V_s A\left(\frac{1+S_R}{2}\right)\cdot \boldsymbol{S} \tag{1}$$

$$V_s = 9.1\times 10^{-6}\ \mathrm{N/m^2} \tag{2}$$

$$\Delta \boldsymbol{M_d} = \int_0^{24h} \boldsymbol{R}\times \boldsymbol{F}_{\mathbf{sp}}\,\mathrm{d}t \tag{3}$$

where $\boldsymbol{F}_{\mathbf{sp}}$ (N) is external force applied in the satellite panel, $V_s(\mathrm{N/m^2})$ is the solar pressure constant, $A$ ($\mathrm{m^2}$) is the area that is normal to the sun position unit vector, $S_R$ is specular reflectivity, $\boldsymbol{S}$ is the sun position unit vector in the Earth-centered inertial (ECI) coordinate, $\Delta\boldsymbol{M_d}$ (Nms) is accumulated momentum during one day in ECI coordinate, and $\boldsymbol{R}$ (m) is the moment-arm vector.

The disturbance torque due to solar radiation pressure is applied in the sun's direction. Equation (3) represents the total accumulated momentum due to solar radiation disturbance torque [6]. In this

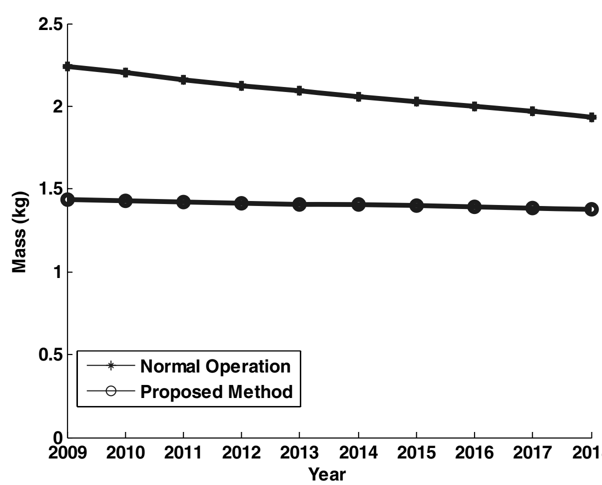


Fig. 3 Consumption of propellant mass for momentum dumping.

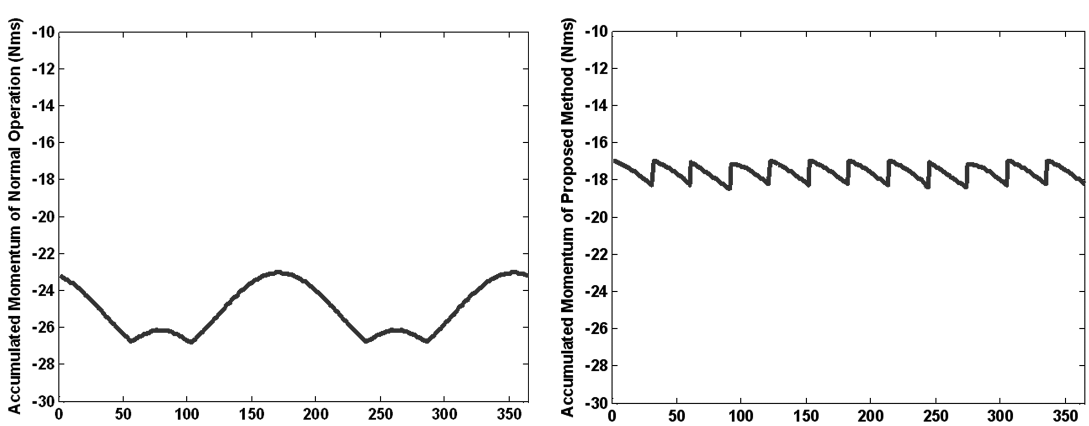


Fig. 2 $X$-axis accumulated momentum during 1 yr.

**Table 4 Efficiency of momentum dumping (solstice, beginning of life)**

| | Normal operation | Relocation of propellant tank | Repositioning of solar array | Solar array offset angle | Total |
|---|---|---|---|---|---|
| Accumulated momentum, Nms/day | 23.03 | 21.44 | 21.43 | 22.46 | 15.21 |
| Efficiency, % | 0 | 6.90 | 6.93 | 22.46 | 33.93 |

**Table 5 Efficiency of momentum dumping (equinox, beginning of life)**

| | Normal operation | Relocation of propellant tank | Repositioning of solar array | Solar array offset angle | Total |
|---|---|---|---|---|---|
| Accumulated momentum, Nms/day | 26.14 | 24.56 | 25.92 | 20.29 | 18.75 |
| Efficiency, % | 0 | 6.03 | 0.83 | 22.36 | 28.26 |

**Table 6 COMS specific parameters**

| COMS specific parameters | Value |
|---|---|
| $Ma_{\mathrm{BOL}}$ | 1554 kg |
| $I_{\mathrm{sp}}$ | 317 s |
| $g$ | 9.80665 m/s |

**Table 7 Velocity increments for north-south station keeping**

| Year | Yearly N/S $\Delta V$, m/s |
|---|---|
| 2009 | 49.9 |
| 2010 | 48.3 |
| 2011 | 46.4 |
| 2012 | 44.4 |
| 2013 | 42.6 |
| 2014 | 41.3 |
| 2015 | 40.7 |
| 2016 | 40.9 |
| 2017 | 41.9 |
| 2018 | 43.4 |

simulation, it is assumed that COMS is composed of seven panels (i.e., six body panels and one solar array panel).

For application of the relocation of mass center of the spacecraft by the blowdown method, the satellite mass properties are required. Figure 1 shows the body-fixed coordinate and the Earth-centered inertial coordinate. As the propellant is consumed, the mass center of COMS changes. Table 1 shows the change in the variation of the mass center achieved by the relocation of the propellant tank.

There is the effect of the orthogonal positioning of the solar array. COMS can maintain its power capacity at over 75% for a maximum discharge time of 90 min and has the maximum Earth eclipse time of 72 min. If the charge time is extended, the time for the orthogonal repositioning of the solar array can be extended. In this study, the discharge time is assumed as 81.5 min, which is the value between 72 and 90 min.

The electric power properties should be analyzed to determine the offset angle. The maximum applied offset angle changes during the satellite's lifetime, because the daily power yield decreases from the beginning to the end of the satellite's lifetime. Table 2 shows COMS electronic unit property, comparing daily power yield with daily power requirement. In the analysis of the power system, the available offset angle is calculated. Table 3 shows the maximum possible offset angle according to the COMS lifetime. As the power yield capability decreases during the satellite's lifetime, the available off set angle also decreases.

Tables 4 and 5 show the effects of the proposed method on COMS. If the proposed methods are applied, then accumulated momentum can be reduced by 33.93% at the solstice and by 28.26% at the equinox.

Figure 2 shows the variation in accumulated momentum in 1 year. The variation and level in momentum of the proposed method are less than those of the normal operation. The total accumulated momentum is reduced, and the equivalent momentum all year round increases the operational efficiency of the satellite control.

The propellant property is analyzed. COMS consumes propellant during the on-station mode for north–south station keeping, east–west station keeping, and momentum dumping. The propellant consumption mass is calculated by Eq. (4). Table 6 shows COMS specific parameters for calculating the propellant consumption mass. In actual operation, the specific impulse is reduced for the satellite's lifetime, but during the simulation, the specific impulse is assumed as a constant value [7]:

$$\Delta Ma = Ma_{\mathrm{before}}\left(1 - \exp\left(-\frac{\Delta V}{I_{\mathrm{sp}} \cdot g}\right)\right) \tag{4}$$

where $\Delta Ma$ (kg) is mass difference, $Ma_{\mathrm{before}}$ (kg) is initial mass, $\Delta V$ (m/s) is velocity difference, $I_{\mathrm{sp}}$ (s) is specific impulse, and $g$ (m/s$^2$) is a gravity constant.

The increments in velocity for east–west station keeping for 2009–2018 are yearly E/W $\Delta V = -1.91$ m/s. Table 7 shows the yearly required velocity increments for north–south station keeping. Table 8 shows the velocity increments for momentum dumping. For the equivalent use of three thrusters, the wheel offloading time range

**Table 8 Velocity increments for momentum dumping**

| Offloading | Period 1 (11 Mar. to 15 July) | Period 2 (14 Nov. to 10 Mar.) | Period 3 (16 July to 14 Nov.) |
|---|---|---|---|
| First offloading $\Delta V_X$, m/s | $-7.75 \times 10^{-5}$ | $-4.61 \times 10^{-5}$ | $-1.58 \times 10^{-3}$ |
| First offloading $\Delta V_Y$, m/s | $-6.51 \times 10^{-3}$ | $-3.87 \times 10^{-3}$ | $-9.67 \times 10^{-3}$ |
| First offloading $\Delta V_Z$, m/s | $-1.82 \times 10^{-3}$ | $-1.08 \times 10^{-3}$ | $1.93 \times 10^{-3}$ |
| Second offloading $\Delta V_X$, m/s | $-8.05 \times 10^{-4}$ | $1.57 \times 10^{-3}$ | $6.20 \times 10^{-4}$ |
| Second offloading $\Delta V_Y$, m/s | $-4.93 \times 10^{-3}$ | $-7.62 \times 10^{-3}$ | $-3.01 \times 10^{-3}$ |
| Second offloading $\Delta V_Z$, m/s | $9.83 \times 10^{-4}$ | $1.36 \times 10^{-3}$ | $5.39 \times 10^{-4}$ |
| Daily sum, m/s | 0.0119 | 0.0119 | 0.131 |
| Yearly wheel offloading $\Delta V$, m/s | | 4.49 | —— |

consists of three periods, as shown in Table 8. COMS performs wheel offloading twice a day, but the performance time is changed according to the season. It is assumed that COMS is located at 128.2°E when analyzing the increments in velocity; each increment is used in calculating the propellant mass, because the propellant for momentum dumping is associated with the total satellite mass.

Figure 3 shows the consumed propellant mass for the cases of normal operation and the applied method. Whereas the consumed propellant needed for momentum dumping is 20.80 kg for normal operation, only 14.07 kg consumption is needed for the proposed methods. The proposed methods save a total propellant mass of 6.73 kg, with a 32.3% improvement of efficiency. The extra propellant can be used to extend the satellite's operation time.

## IV. Conclusions

As the market for satellites grows, the demand for the satellites that are capable of performing various missions simultaneously increases. Multipurpose satellites sometimes have a single solar array because of other assigned requirements. In this Note, the momentum mitigation method for a single-solar-array satellite is introduced and analyzed. In a single-solar-array satellite, momentum accumulation lowers the propellant efficiency of the satellite. The propellant mass that is needed for momentum dumping increases to compensate the momentum, and the mission time is reduced by performing momentum dumping. To reduce momentum accumulation, the relocation of the mass center of the spacecraft by blowdown, orthogonal positioning of solar array, and solar array offset-angle control methods are proposed. The proposed methods do not require extra propellant. These methods reduce the total launch mass. The availability of proposed methods reduces propellant consumption and extends satellite lifetime. The simulation results show that the propellant for momentum dumping can be reduced by 32.3%.

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