Magnetic Unloading Scheme for Improving Pointing Performance of Astronomy Satellites

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Abstract

This paper describes magnetic unloading scheme effective for improving pointing performance of astronomy satellites. In order for achieving pointing accuracy in the order of arc-seconds and pointing stability of sub arc-second level, even magnetic unloading scheme should be designed so that it might not be a disturbance source, and yet it can cancel surplus angular momentum in momentum wheels (MWs) or reaction wheels (RWs) efficiently. The design approach for improving pointing performance is based on the method that total torque acting on a satellite is minimized, including disturbance torque, wheel reaction torque, and unloading torque induced by magnetic torquers (MTQs). The discussion on the magnetic unloading scheme covers unloading laws that determine the period and the magnitude of MTQ drive, and its driving electronics. The study shows that an unloading law already proposed by the authors is effective for reducing the total torque by utilizing predicted or estimated disturbance torque. This results in improving pointing accuracy. The study also shows that requirements on MTQ drive can be established in terms of dipole command resolution, magnetic field calculation or measurement resolution, and its update period. It is suggested that a cooperative control by RW/MW is required in addition to the magnetic unloading scheme for further improvement in pointing performance.

Key words: Attitude control, Magnetic unloading, Pointing accuracy, Pointing stability.

Introduction

The pointing requirements of ISAS astronomy satellites have become more and more stringent, until the pointing accuracy in the order of arc-seconds and pointing stability of sub arc-second should be realized. Fig. 1 depicts the requirements on pointing accuracy and pointing stability for the past and the near future astronomy satellites of ISAS. The requirements have been successfully achieved so far for the satellites already launched. However, the achievement of the pointing accuracy for the near future satellite should involve suppression of structural deformation and/or thermal distortion as well as improvement in attitude control performance. The pointing stability should also be considered in the same way when the sub arc-second stability is required. Especially, the requirement on the pointing stability will become so tremendously enhanced that attitude stability should be improved by an appropriate approach.

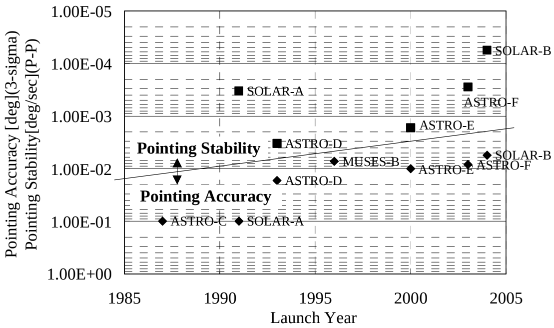

Fig. 1 Pointing Requirements

Under this situation, magnetic unloading scheme should also be improved so that it might not induce disturbance that deteriorates pointing performance, and yet it can cancel surplus angular momentum in MWs/RWs efficiently. Most magnetic unloading schemes have been dedicated to unloading efficiency which will reduce MTQ dimension, its weight and power consumption rather than to improvement in pointing performance as far as the unloading torque does not interfere with the primary task of achieving good attitude control. However, the enhanced requirements on pointing accuracy and pointing stability have made it inevitable to design the unloading scheme

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so that it helps improve the pointing performance.

The design approach for improving pointing performance is based on the method that total torque acting on a satellite is minimized. The total torque includes disturbance torque such as gravity gradient torque and aerodynamic torque, magnetic unloading torque induced by MTQs, and reaction control torque generated by MWs/RWs. Since the latter two are control torque, they can be generated so as to compensate for the disturbance torque as far as it can be estimated or calculated by an appropriate method.

The magnetic unloading scheme discussed in this paper consists of unloading laws that determine the period and magnitude of MTQ drive, and its driving electronics. The unloading laws are basically categorized into bang-bang laws and continuous laws. The two categories are compared qualitatively from the standpoints of achieved performance, required electronics and unloading efficiency. In spite of the simplicity of bang-bang laws and its driving electronics, we need to apply continuous unloading for achieving improved pointing performance. Therefore, the continuous unloading is further studied so that it can suppress disturbance torque, and that its driving will not induce disturbance that might deteriorates the pointing performance. Then, the requirements on MTQ drive are studied in details for continuos unloading.

This paper is organized as follows. At first, specifications on pointing performance are introduced for the near future astronomy satellites, ASTRO-F and SOLAR-B. Then criteria for disturbance torque are calculated according to the specifications. In the next section, an attitude controller design approach is introduced which will lead to improve the pointing performance. The following section describes the magnetic unloading scheme including a brief explanation of unloading laws and MTQ driving electronics. The two aspects of the unloading scheme will further be studied in the subsequent two sections, especially for continuous unloading with disturbance suppression and the requirements on MTQ drive. They are followed by a summary of the two studies. Conclusions are found in the final section.

Criteria for Disturbance Torque

In this section, pointing specifications are introduced first for ASTRO-F and SOLAR-B, the near future astronomy satellites of ISAS. Then, assuming typical attitude controllers for the two satellites, criteria for disturbance torque are calculated. The criteria will be utilized in the following sections to compare them with the external torque acting on the satellites and the disturbance torque induced by magnetic unloading.

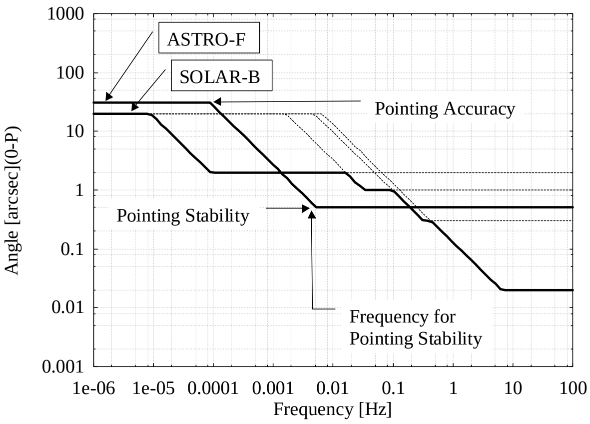


Fig. 2 Pointing Specification

Fig. 2 shows the pointing specifications for ASTRO-F and SOLAR-B with respect to frequency. Regarding to ASTRO-F, the specification in a lower frequency region corresponds to pointing accuracy, while that in a higher frequency region indicates pointing stability. The intermediate frequency range basically indicates pointing stability. In this range, the period in which the pointing stability is specified is of the order or less than the inverse of the frequency, and the specification becomes larger as the frequency becomes smaller until it reaches to the pointing accuracy. There exist several pointing requirements for SOLAR-B depicted by the dashed lines in Fig. 2, and each of them is defined in a similar manner. The bold line for SOLAR-B is the severest requirement among them for each frequency.

In the higher frequency range, structural resonance will make the specification severer than plotted. Sometimes, we need to make the specifications divided by more than 50. However, the number is depending on structure design for each satellite. Therefore, the effect is not taken into account in Fig. 2.

Fig. 3 shows a general control system block diagram, in which $\boldsymbol{P}$ is a plant, $\boldsymbol{C}$ is a controller, $\boldsymbol{d}$ is disturbance torque, and $\boldsymbol{\theta}$ is pointing angle. By taking $\boldsymbol{\theta}$ to be the pointing specification, the criteria for the disturbance torque can be derived as,

$$\boldsymbol{d} = \boldsymbol{P}^{-1}\left(\boldsymbol{I} + \boldsymbol{PC}\right)\theta \quad . \tag{1}$$

By assuming a controller based on PD controller whose formula is expressed as

$$\boldsymbol{C} = \boldsymbol{I_B}\left(2\varsigma_c\omega_c\, s + s^2\right), \tag{2}$$

and by assuming the parameters of the controllers for the two satellites as listed in Table 1, the criteria can easily be obtained and the results are plotted in Fig. 4.

For the region where the frequency is more than ω_c (i.e.

Table 1 Parameters of Controllers

	ASTRO-F	SOLAR-B
ω_C	0.03 [Hz]	0.1 [Hz]
ξ_C	0.5	0.5
I_B	1000 [$kg \cdot m^2$]	1000 [$kg \cdot m^2$]

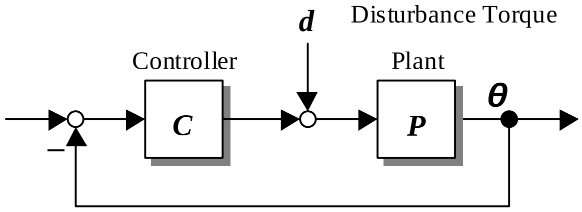


Fig. 3 General Control System Block Diagram

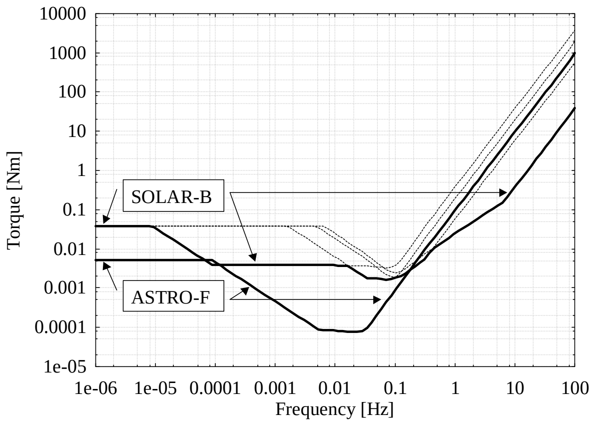


Fig. 4 Criteria for Disturbance Torque

control frequency), the torque acting on the satellites should absolutely be less than the criteria because the controllers cannot compensate it. For the region where the frequency is less than ω_c, the torque should be less than the criteria, otherwise the criteria should be modified by incorporating a stronger feedback attitude control (i.e. larger ω_c). However, since ω_c is usually designed to be at its maximum by considering limitations such as those caused by flexibility of solar arrays and fuel sloshing, it is less possible to make ω_c any larger. Therefore, the disturbance should be reduced regardless of its frequency by an appropriate method if it exceeds the criteria.

Controller Design Approach

In this section, a design approach for a satellite attitude controller is described which leads to the improvement in pointing performance with an efficient magnetic unloading. Fig. 5 illustrates a typical attitude control system block diagram. It consists of a controller and a plant that is divided into body dynamics and wheel dynamics. For simplicity, any of the complicated blocks are not included in the diagram such as flexible appendages and fuel sloshing. Of course, these elements should be taken into account in designing feedback control law and they often put severe limitations on the feedback control gain, thus on the achievable performance of the attitude control system.

The main function of the controller is to generate a wheel torque command ($\boldsymbol{T_C}$) for controlling MWs/RWs and to generate a magnetic dipole command ($\boldsymbol{m}$) for driving MTQs which induces $\boldsymbol{T_M}$ by an interaction with geomagnetic field ($\boldsymbol{B}$). The wheel torque command can be calculated by adding a feed forward torque ($\boldsymbol{T_{FF}}$) to a feedback torque ($\boldsymbol{T_{FB}}$). The wheels have friction torque ($\boldsymbol{T_f}$) depending on their rotational rate. Therefore, the wheel torque command subtracted by the wheel friction torque will act on the satellite (denoted by $\boldsymbol{T_W}$), and the reaction torque (=-$\boldsymbol{T_W}$) will act on the wheels. If the wheel control has a rate feedback loop (the rate feedback loop is not explicitly depicted in Fig. 5) for stabilizing wheel rotational rate, we regard that another feedback torque is added to $\boldsymbol{T_C}$ so as to compensate the friction torque.

The magnetic dipole induced by MTQs interacts with the geomagnetic field ($\boldsymbol{B}$) to generate $\boldsymbol{T_M}$. Magnetic dipole induced other than MTQs or permanent magnetic residual also generates torque. We regard such torque as one of the factors of disturbance torque $\boldsymbol{T_d}$.

The gyro torque ($\boldsymbol{T_g}$) in the body dynamics is generated if the angular momentum in the wheels ($\boldsymbol{h_W}$) is not zero, or the body angular rate ($\boldsymbol{\omega_B}$) is not aligned to the principal axis of the moment of inertia of the body.

As explained above, the total torque acting on the satellite is expressed as

$$\boldsymbol{T}_{total} = \boldsymbol{T}_W + \boldsymbol{T}_M + \boldsymbol{T}_d + \boldsymbol{T}_g \ , \tag{3}$$

or equivalently,

$$\boldsymbol{T}_{total} = \boldsymbol{T}_{FB} + \boldsymbol{T}_{FF} + \boldsymbol{T}_M + \boldsymbol{T}_f + \boldsymbol{T}_d + \boldsymbol{T}_g \ . \tag{4}$$

As we explained previously, our design goal is to minimize the total torque acting on the satellite written in Eq. (4). For this purpose, a controller design approach is proposed as follows:

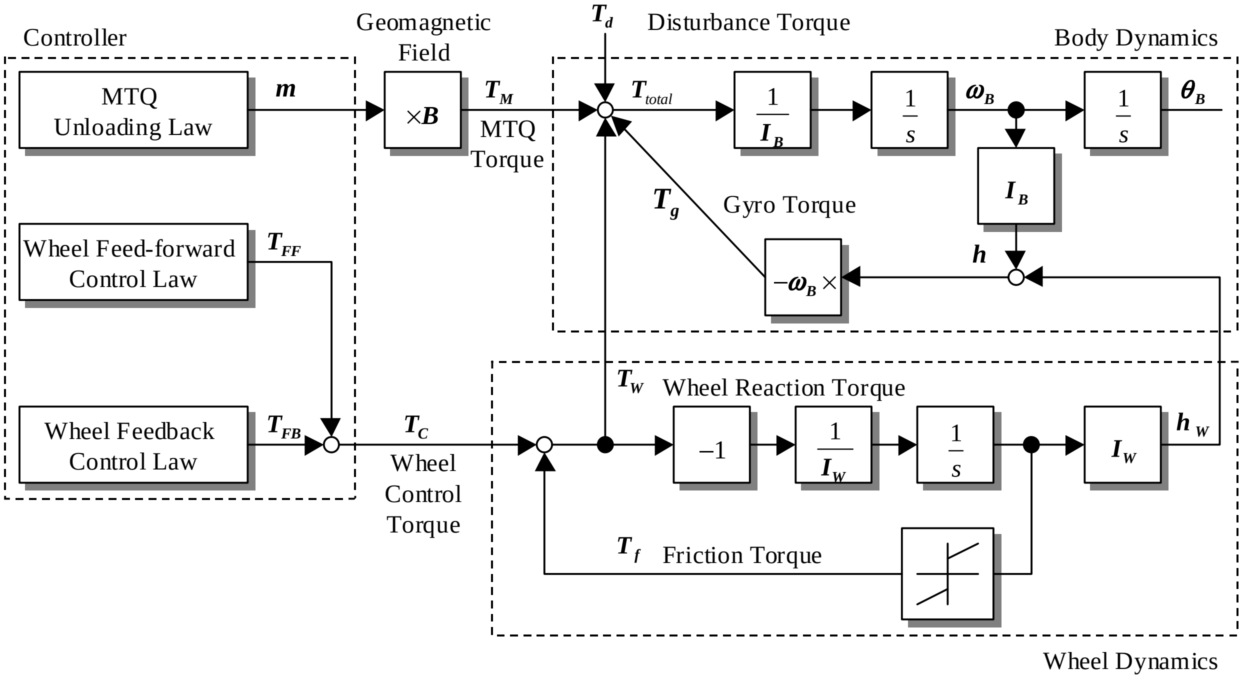


Fig. 5 Attitude Control System Block Diagram

- To stabilize attitude of a satellite by $\boldsymbol{T}_{FB}$ with maximized pointing performance.
- To minimize the total torque in Eq. (4) so as to satisfy the criteria for disturbance torque in Fig. 4.
- To unload surplus angular momentum in MWs/RWs with appropriate efficiency.

Our concern at this point is stressed on the latter two approaches, since we regard that the feedback control is optimized with maximized pointing performance within the restriction that pointing control never diverges. Even if a stronger feedback control can be applied, it might require additional hardware or larger actuators, and thus cause increase in weight, power or cost. Because of this reason, we should take the second approach instead of the first approach for the final design goal.

For the purpose of achieving the second approach, control torque $\boldsymbol{T}_{FF}+\boldsymbol{T}_{FB}+\boldsymbol{T}_M$ should be generated so as to compensate the others, i.e. $\boldsymbol{T}_f+\boldsymbol{T}_d+\boldsymbol{T}_g$. It might be probable that the control torque itself is greater than the criteria. It does happen if bang-bang control is applied as an unloading law. In this case, $\boldsymbol{T}_M$ might violate the criteria at the transient when the MTQ drive is turned on or turned off, and an attempt could be possible to cancel $\boldsymbol{T}_M$ by $\boldsymbol{T}_{FF}$. However, as will be shown later, the bang-bang unloading is not suitable for achieving high pointing performance. Therefore, we will not consider such a case, and we assume that the total control torque $\boldsymbol{T}_{FF}+\boldsymbol{T}_{FB}+\boldsymbol{T}_M$ should be generated to cancel $\boldsymbol{T}_f+\boldsymbol{T}_d+\boldsymbol{T}_g$. Especially, the cancellation of gyro torque $\boldsymbol{T}_g$ by feed forward torque $\boldsymbol{T}_{FF}$ is generally applied as de-coupling for a three-axis stabilized satellite.

The third approach will be realized by a variety of unloading laws. One of them is an unloading law proposed by the authors and its effect will be demonstrated later.

Magnetic Unloading Scheme

The magnetic unloading scheme discussed in this section covers unloading laws that determine a period and magnitude of MTQ drive, and its driving electronics. These two aspects of the scheme are discussed from the standpoints of disturbance sources as well as unloading efficiency. The suppression of the disturbance is sometimes contradictory to pursuing efficiency, and we need to make a trade-off for an actual application, depending on the requirement on pointing accuracy and applicable resources such as weight and power.

Unloading Law

The simplest unloading law is a bang-bang unloading by which the MTQ drive is just turned on at its maximal drive current to activate unloading and just turned off to cease unloading. The unloading law has an advantage that the required driving electronics is very simple and that the driving efficiency is relatively high. Actually, the driving electronics is just an on-off switch realized by a relay or a transistor. On the other hand, the unloading law has a disadvantage that a relatively large disturbance is induced at the on-to-off or off-to-on transition. For the purpose of suppressing the disturbance, pre-feed forward MW/RW cooperative control has been applied.

Fig. 6 plots a flight data of HALCA (or MUSES-B launched in 1997), which shows pointing error by the bang-bang unloading. The horizontal axis indicates time (1division=120[sec]) and the vertical axes indicate pointing errors. The pre-feed forward MW/RW control was applied a few seconds prior to the initiation of MTQ unloading. Without the pre-feed forwarded torque, the pointing error might be more than 0.004 [deg], and the MW/RW pre-feed forward control could reduce the pointing error. However, about 0.002 [deg] pointing error still remained even after the MW/RW cooperative control was tuned to get the best results. This implies that, as far as bang-bang unloading is applied, the induced disturbance cannot entirely be compensated by MW/RW. This is mainly because the transient time constant of MTQ is relatively long while the time constant of MW/RW control is relatively short. If we apply the unloading method to the satellites of ASTRO-F and SOLAR-B, the pointing error will become more than 0.01 [deg] because the external disturbance is larger than that for HALCA, and thus the MTQ size is bigger. Therefore, it is evident through flight experience and its associated study that the bang-bang control cannot be applied for the astronomy satellites that require higher pointing accuracy, and that we need to apply continuous unloading instead of bang-bang unloading.

The continuous unloading has an advantage that the driving disturbance is small. Actually, it is only affected by a command resolution that determines MTQ driving current. The required resolution will be studied later. On the other hand, the continuous unloading has a disadvantage that driving efficiency is relatively low. The driving electronics for the continuous unloading will be explained in the following subsection.

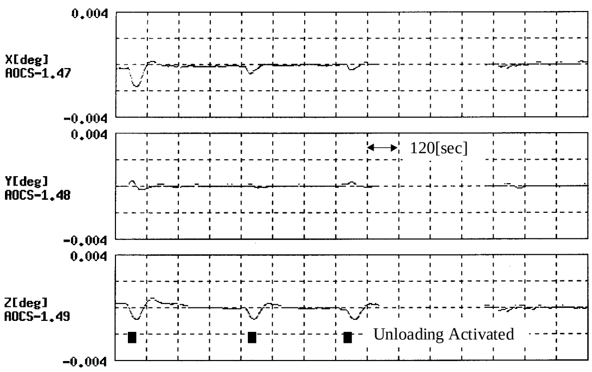


Fig. 6 Pointing Error by Bang-bang Unloading

MTQ Driving Electronics

In this subsection, MTQ driving electronics is explained which allows us to realize continuous unloading. From the standpoint of the technology of the art, there exist mainly two regulating circuits that control MTQ driving current continuously, one is a series regulator and the other is a switching regulator.

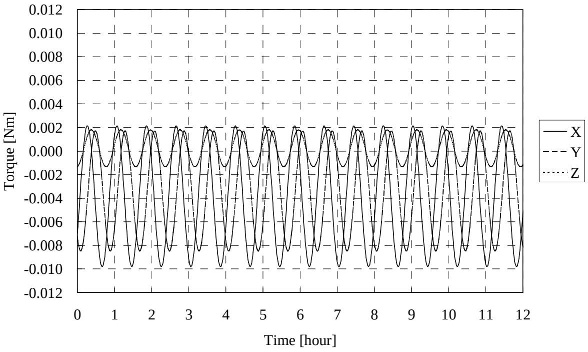
The series regulator is a transistor-based or FET-based circuit, and the driving current is controlled by the device impedance. In other word, even when the current becomes smaller, the total power consumption cannot be reduced linearly because the ratio of additional power consumption in the devices to the total power becomes larger. Thus, the efficiency for MTQ drive is relatively not so high as other circuits such as the on-off switch for bang-bang unloading and the switching regulator for continuous unloading described below.

The switching regulator is a circuit that switches on and off the MTQ current periodically in a high frequency more than 100 [Hz]. In the circuit, the duty and/or the frequency of on/off cycle is controlled, so that the mean current can be controlled linearly. Again, the on-off device is a transistor or a FET, but the operational condition of the devices is in the saturation region, and the device impedance is at its minimal condition. Therefore, the efficiency is relatively high compared with the series regulator. The disadvantage of the switching regulator is that it has a ripple current that might be another disturbance source. However, as we will show later, the ripple current does not affect the pointing performance at all.

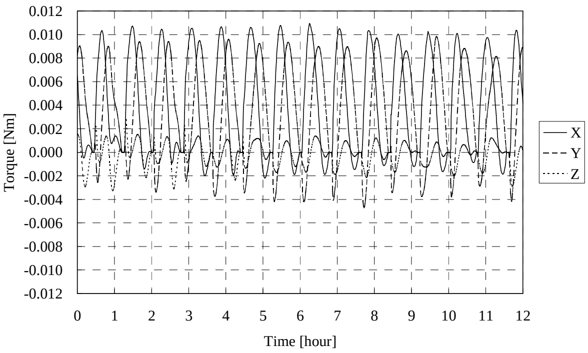
Both the series regulator and the switching regulator can control the current linearly. However, the advantage in efficiency for the switching regulator will reduce the power consumption of MTQ drive, thus it will help reduce the dimension and weight of power supply system of a satellite. This benefit will be much enhanced when a satellite becomes larger, and we will adopt the switching regulator despite of somewhat sophisticated electric circuit.

Continuous Unloading Law with Disturbance Suppression

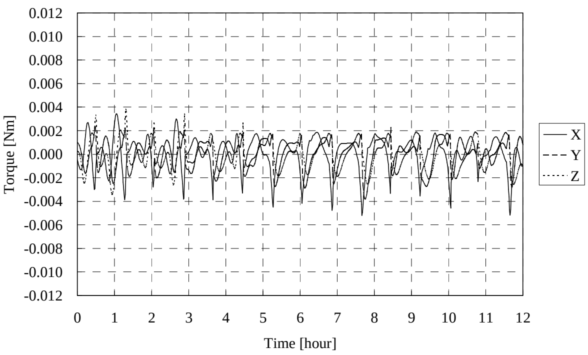
A conventional and simple continuous unloading law is a cross product of surplus angular momentum and magnetic field multiplied by a constant control gain[1]. This is, so we call, an instantaneous law in a sense that it considers just the instantaneous surplus angular



(a) External Disturbance Torque



(b) Unloading Torque



(c) Residual Torque (= (a) + (b))

Fig. 7 Disturbance Suppresion by Unloading

momentum, and somewhat sacrifices unloading efficiency. More sophisticated unloading laws have been presented mainly for improving unloading efficiency rather than for improving pointing performance. One of them is the unloading law proposed by the authors[2]. Though the unloading law was originally designed so as to increase the unloading efficiency, it also helps improve the pointing accuracy.

The basic idea of the unloading law is that MTQ unloading torque is generated so as to cancel the disturbance torque acting on a satellite, and to reduce the surplus angular momentum stochastically. Of course, this is valid only for the directions perpendicular to the geomagnetic field, because MTQs can generate torque only about such directions. The disturbance torque necessary for the unloading law can be estimated by monitoring the angular momentum in MWs/RWs, or it can be calculated based on a mathematical model.

Fig. 7 (a), (b) and (c) show simulation results, proving that the unloading law can suppress the external disturbance torque. Fig. 7 (a) plots an external disturbance torque. The conditions of the simulation are identical to those for ASTRO-E in Ref.1. By applying the unloading law presented in Ref. 1, the unloading torque can be generated as depicted in Fig. 7 (b). The residual torque (= (a) + (b)) is plotted in Fig. 7 (c). By comparing Fig. 7 (a) and Fig. 7 (c), we can see that the unloading torque can be reduced by more than 50% by the unloading law.

Table 2 Error Sources for Residual Torque

Error Sources	Torque [Nm]
External torque estimation or modeling error	0.0005
Unloading torque for stochastically reducing surplus angular momentum	0.001
External disturbance torque parallel to geomagnetic field	0.003

The residual torque in Fig. 7 (c) is due to the external torque estimation or modeling error, unloading torque for stochastically reducing surplus angular momentum, and the external disturbance torque parallel to geomagnetic field. These factors for residual torque are estimated and listed in Table 2. Though it is impossible to suppress the external disturbance torque parallel to the geomagnetic field by MTQs, further suppression is possible by applying MWs/RWs cooperative control. Therefore, further improvement in pointing performance is expected. This issue is left for the future study since the suppression of the external disturbance torque is good enough for the two satellites, ASTRO-F and SOLAR-B.

Requirements on MTQ Drive

In this section, the disturbance torque induced by a continuous unloading is compared with the criteria for disturbance torque in Fig. 4 that assures the pointing performance for the two astronomy satellites, ASTRO-F and SOLAR-B. We assume that the continuous unloading discussed here is controlled using an onboard computer in which all the quantities are digitized. Therefore, the disturbance due to the continuous unloading is caused not only by the ripple current when the switching regulator is adopted, but also by resolution of command that determines the driving current in the MTQs, by the magnetic field calculation resolution or measurement resolution, and by the magnetic field update period. By the study, the requirements on such disturbance sources are established.

The MTQs generating torque ($\boldsymbol{T_M}$) is expressed as

$$\boldsymbol{T_M} = \boldsymbol{m} \times \boldsymbol{B}, \qquad \textbf{(5)}$$

where $\boldsymbol{m}$ is magnetic dipole strength generated by the MTQs and $\boldsymbol{B}$ is geomagnetic field. By taking the variations for the both sides of Eq. (5), we obtain

$$\Delta \boldsymbol{T_M} = \Delta \boldsymbol{m} \times \boldsymbol{B} + \boldsymbol{m} \times \Delta \boldsymbol{B}, \qquad \textbf{(6)}$$

where $\Delta\boldsymbol{m}$ is a sum of the command resolution for the magnetic dipole and the ripple caused by the switching regulation, and $\Delta\boldsymbol{B}$ is a sum of the geomagnetic field calculation or measurement resolution and the deviation caused by geomagnetic field update period. According to the study for the ASTRO-F, the required magnetic dipole strength is 300 [Am^2], and the maximum geomagnetic field is 5×10^{-5} [T] on its nominal orbits. By using these values, the requirements on MTQ drive will be established in the following subsections.

Command Resolution

As is mentioned above, the MTQ drive is not exactly continuous but it has a discrete step determined by the command resolution. The command resolution is determined not only by the precision of the onboard computer but also by the resolution of D/A converter if it is used in the MTQ driving electronics. The command resolution discussed here includes both the factors.

Because of the discreteness, MTQ dipole strength is also a discrete one as far as we consider a steady state in which the current in a MTQ settles to a certain value. The Fourier component or the frequency range of the command is subject to both how to make the command, and the computer calculation time step. However, in this subsection, we will take the most severe condition that the command has a wide range of frequency between an orbital frequency of a satellite and the computer calculation frequency.

With this condition taken into account, the disturbance torque induced by the discrete command should be less than 0.00008 [Nm] according to the criteria shown in Fig. 4. We regard this value as 3-sigma. In general, the discrete variable whose step is d has an equivalent random noise and its normal distribution is expressed as

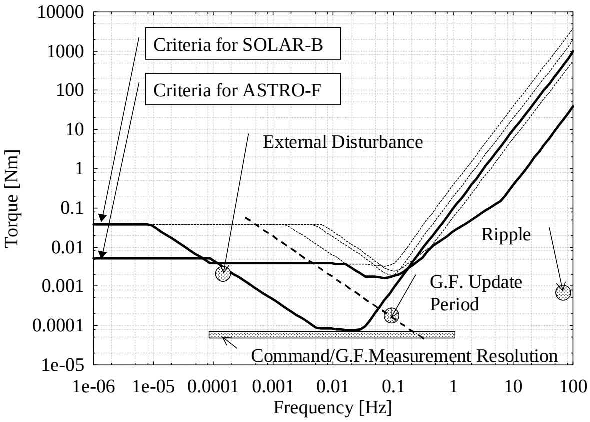


Fig. 8 Disturbance Torque

$$\sigma_d = \frac{1}{\sqrt{12}} d \ . \qquad \textbf{(7)}$$

Therefore, the torque resolution $\Delta\boldsymbol{T}$ should be less than $0.00008 \times \sqrt{12}/3 = 0.0000924$[Nm]. Then the command resolution $\Delta\boldsymbol{m}$ can be calculated as

$$\Delta \boldsymbol{m} \le \frac{\Delta \boldsymbol{T}}{\boldsymbol{B}} \le \frac{0.0000924}{5 \times 10^{-5}} = 1.85 \ [\mathrm{Am}^2] \ . \qquad \textbf{(8)}$$

On the other hand, the maximum dipole strength is 300 [Am^2]. Therefore, the command should have more than 300/1.85 = 162 steps. It means that the command shall have a digit better than 8 bits. The requirement also implies that total command resolution, including both the command issued from the onboard computer and the D/A conversion, shall be better than 8 bits.

Geomagnetic Field Measurement Resolution

The minimum $\Delta\boldsymbol{B}$ can be calculated in a similar way as

$$\Delta \boldsymbol{B} \le \frac{\Delta \boldsymbol{T}}{\boldsymbol{m}} \le \frac{0.0000924}{300} = 308 \times 10^{-9} \ [\mathrm{T}] \ . \qquad \textbf{(9)}$$

On the other hand, the range of the geomagnetic field is -50000 to +50000 $\times 10^{-9}$ [T]. Therefore, the geomagnetic field should have more than 100000/308 = 187 steps. It also means that the measurement shall have better than 8-bit resolution.

Geomagnetic Field Update Period

The geomagnetic field varies as the satellite moves on its orbit, and the primary sinusoidal component has an orbital period for earth pointing or a half of it for inertial pointing. As far as update period Δt of several seconds

Table 3 Characteristic of the switching regulator

Item	Value
Switching frequency	More than 100 [Hz]
Ripple current	Less than 5%

is considered, the maximum change in the geomagnetic field can be estimated as follows:

$$\Delta \boldsymbol{B} = \begin{cases} 5\times10^{-8}\,\Delta t & \text{(Earth pointing)} \\ 1\times10^{-7}\,\Delta t & \text{(Inertial pointing)} \end{cases} \ [\mathrm{T}]\,, \tag{10}$$

where Δt in [sec]. By assuming that $\boldsymbol{m}$ = 300 [Am^2] and by taking $f = 1/\Delta t$ [Hz], the torque error $\Delta \boldsymbol{T}$ can be calculated as

$$\Delta \boldsymbol{T} = \begin{cases} 1.5\times10^{-5} / f & \text{(Earth pointing)} \\ 3\times10^{-5} / f & \text{(Inertial pointing)} \end{cases} \ [\mathrm{Nm}]\,. \tag{11}$$

The dotted bold line in Fig. 8 plots the above condition for ASTRO-F. In order for satisfying the criteria, the geomagnetic field update frequency shall be more than 0.1 [Hz], or in other word, the update period shall be less than 10 [sec].

Ripple torque

The ripple torque induced by a switching regulator is assessed in this subsection. Table 3 lists characteristics of the switching regular associated with the ripple torque. The resultant ripple torque can be calculated as

$$\left(5\times10^{-5}\right)\times300\times0.05=0.00075[\mathrm{Nm}]\,. \tag{12}$$

The value seems so small compared with the criteria of the disturbance torque as shown in Fig. 8 that we do not have to pay much attention to the ripple torque.

Achieved Pointing Performance

This section summarizes the disturbance torque studied in the last two sections. Again, Fig. 8 shows disturbance torque caused by the factors including external disturbance. We can see that the disturbance torque is less than the criteria. Fig. 9 depicts the achieved pointing performance when we consider the suppression of external disturbance by the proposed unloading law and the requirements on MTQ drive. We can see from the two figures that the attitude deterioration can be within the specifications.

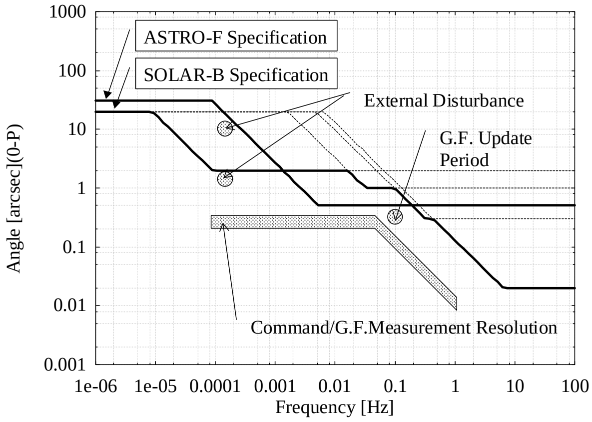


Fig. 9 Achieved Performance

Conclusion

In this paper, magnetic unloading scheme has been studied from the standpoint of improving pointing performance. The design approach for that purpose has been introduced. By applying the unloading law already proposed by the authors, the disturbance torque acting on a satellite is reduced by more than 50%, which leads to suppress pointing error by more than 50%.

MTQ drive has also been studied and the requirements have been established. The study showed that MTQ command resolution should be better than 8 bits, the resolution for geomagnetic field measurement or calculation should be better than 8 bits, and the update period for the geomagnetic field measurement or calculation should be less than 10 [sec].

By applying the unloading scheme presented in this paper, the pointing performance of the two astronomy satellites, ASTRO-F and SOLAR-B, can meet their mission requirements. Further improvement is possible by incorporating a cooperative control with MWs/RWs for the future astronomy satellites that require more stringent pointing performance.

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