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Feedback Control Law Design for the Dual-Spin Turn of Spacecraft

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A new feedback control law design for the dual-spin turn maneuver of spinning spacecraft is discussed. The control law design study is motivated by stability analysis of dual-spin spacecraft. The feedback control law is based on the relationship between nutational stability and system energy associated with the rotational motion of spacecraft and a momentum wheel. The applied torque to the momentum wheel is adjusted in a feedback control form, for which the control law is expressed as a function of spacecraft angular velocity components, as well as the momentum wheel speed. Furthermore, a two-stage control strategy, which consists of conventional open-loop maneuver and a new feedback technique, is developed. The new strategy is verified by simulation study using Koreasat mass property data.

I. Introduction

THE dual-spin spacecraft stability and associated dual-spin turn (DST) maneuver of spacecraft have been studied extensively.[1−13] Basically, the DST maneuver is based on the momentum conservation principle between a spinning momentum wheel (rotor) and spacecraft main body. The result of DST maneuver is attitude change of spacecraft and momentum transfer between the wheel and spacecraft body. Both dual-spin spacecraft and spacecraft employing a momentum wheel for DST maneuver are operated by the principle of gyroscopic effect. The main difference between dual-spin spacecraft stability and DST maneuver lies in the magnitude of the maneuver angle. That is, the DST involves large-angle reorientation of the spacecraft body,[9−13] whereas dual-spin spacecraft stability analysis is usually limited to the small-angle regime. The key issue in dual-spin spacecraft is dynamics and stability analysis in conjunction with the energy dissipation effect. A spinning rotor becomes a counterpart to the nonrotating platform for the dual-spin spacecraft. As is usually the case, the rotor (or wheel) speed is taken to be a constant in dual-spin spacecraft stability analysis.[5−8] On the other hand, the performance of the DST maneuver partially relies on selecting a judicious wheel control torque for the body axis turning maneuver with minimal transverse coupling momentum produced.[5,9−13] Once the wheel speed reaches a certain value, however, a passive damping mechanism is needed for the completion of the maneuver.

An important element in dual-spin spacecraft stability is energy input provided by the spinning rotor. This has brought about the controversial energy sink debate among some investigators.[1−8] When the wheel speed changes, the total system energy may increase or decrease while the total angular momentum remains fixed in the inertial space. A useful physical parameter connected to the stability analysis of dual-spin spacecraft is so-called core energy. The core energy is defined to be the total system energy of a fictitious rigid body, neglecting the relative motion of the rotor.[5−8] The controversial debate on energy sink analysis has experienced considerable progress by taking the rotor kinetic energy into account. This was made possible by the core energy theory. The results of previous studies[5−8] indicate the core energy should decrease for nutational stability despite the increase in total energy.

In parallel with the general open-loop approach in the DST maneuver, there have been several papers discussing active control strategies. Junkins and Turner[9] applied optimal control theory to the DST maneuver. They took a performance index for which the final angular velocity components of the spacecraft body are sought to be minimized. They computed the torque profile of the wheel by solving a nonlinear two-point boundary value problem. Weissberg and Ninomiya[10] used Hubert's[5] core energy to derive a feedback control law, which is designed to decrease the core energy by adjusting wheel torque input. Their approach is essentially similar to the one presented in this paper with a different control law.[10] Kawaguchi et al.[11] applied active control techniques for the DST maneuver of multiwheel configuration. They designed a nonlinear feedback control law with stability guarantee by Lyapunov's direct method. In this approach, the active control technique is shown to be useful for maximum to minimum moment of inertia axes transfer. Hall[12] discussed a time-varying control torque input designed for two-rotor gyrostats. He developed the so-called stationary-platform maneuver,[12] for which the platform angular velocity is minimized by an active control action.

In this study, a new feedback control technique for the DST maneuver is discussed. The momentum wheel speed is adjusted depending on the current dynamic motion of the spacecraft. Therefore, the new control law assumes measuring the angular velocity of the spacecraft and relative wheel speed. Even if this seems to be a disadvantage compared to the pure open-loop type approach, it is still a feasible solution because the body axis angular velocities are easily measured by rate measuring devices. The key idea of the feedback control law design is to minimize the final nutation angle created during the DST maneuver by decreasing the core energy of the system. The core energy has been used for a feedback control law by Weissberg and Ninomiya.[10] The new method in this study also uses core energy, but the control law is derived in a form different from the previous studies.[9−12] The control law is simple to implement, and it takes advantage of both the conventional open-loop approach and a new feedback technique. The new feedback control law uses Lyapunov stability theory.[14]

Two different control laws are investigated and their performance compared. One is a direct feedback control law by Lyapunov's direct method. The Lyapunov function consists of the core energy and the error energy as a function of error between current and final desired angular momentum of the wheel. The other one is a two-stage feedback control law as a combination of typical open-loop strategy

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and a feedback scheme based on so-called pseudocore energy, as will be explained later.

The control law is tested through simulation study using example data. The example data are mass property data taken from Koreasat, a geosynchronous Earth orbit communication satellite launched in 1995. Different sets of inertia properties of the spacecraft are also tested to demonstrate the applicability of the proposed control strategy. In particular, an inverted DST maneuver is tried to test applicability of the new feedback control law.

II. Equation of Motion and Problem Statement

The schematic representation of the DST maneuver of a spacecraft containing a momentum wheel is presented in Fig. 1. The initial spin axis of the spacecraft is assumed to be the $\hat{b}_1$ axis, which is usually the axis of maximum moment of inertia for the normal DST maneuver. In this case, the wheel is assumed to be aligned with respect to the minimum moment of inertia axis. However, throughout the mathematical development of the control law, there is no particular constraint imposed on the relative sizes of the moment of inertia.

The angular momentum of the system including the wheel dynamics, by assuming zero product of inertia of spacecraft body itself, is represented as

$$\hat{\boldsymbol{H}} = I_1\omega_1\hat{\boldsymbol{b}}_1 + I_2\omega_2\hat{\boldsymbol{b}}_2 + (I_3\omega_3 + J_w\Omega)\hat{\boldsymbol{b}}_3 \tag{1}$$

where J_w is the moment of inertia of the wheel along the spin axis, Ω is the relative wheel speed along the $\hat{\boldsymbol{b}}_3$ axis, and $\hat{\boldsymbol{b}}_i$ $(i = 1, 2, 3)$ is a unit vector along the principal body axes. The system inertial momentum satisfies

$$I_i = I_i^s + I_i^*, \qquad i = 1, 2, 3$$

where we assume the center of mass of the spacecraft and wheel coincide to simplify the analysis. I_i^s is the principal moment of inertia of the spacecraft itself without the wheel, and I_i^* is the principal momentum of inertia of the wheel. For notational clarity, we use J_w instead of I_3^* from now on.

The angular momentum vector in Eq. (1) produces a governing equation of motion as

$$\frac{{}^N\mathrm{d}\hat{\boldsymbol{H}}}{\mathrm{d}t} = \frac{{}^B\mathrm{d}\hat{\boldsymbol{H}}}{\mathrm{d}t} + {}^B\hat{\boldsymbol{\omega}}^N \times \hat{\boldsymbol{H}} = \hat{\boldsymbol{L}} \tag{2}$$

where ${}^N(\,)$ and ${}^B(\,)$ represent both inertial and body frame quantities, respectively, ${}^B\hat{\boldsymbol{\omega}}^N = \omega_1\hat{\boldsymbol{b}}_1 + \omega_2\hat{\boldsymbol{b}}_2 + \omega_3\hat{\boldsymbol{b}}_3$ is the angular velocity vector of the spacecraft body axes with respect to the inertial frame of reference, and $\hat{\boldsymbol{L}}$ is the vector of applied torque. The result of Eq. (2) is expanded into

$$\begin{aligned} I_1\dot{\omega}_1 + (I_3 - I_2)\omega_2\omega_3 + J_w\Omega\omega_2 &= L_1 \\ I_2\dot{\omega}_2 + (I_1 - I_3)\omega_1\omega_3 - J_w\Omega\omega_1 &= L_2 \\ I_3\dot{\omega}_3 + (I_2 - I_1)\omega_1\omega_2 + J_w\dot{\Omega} &= L_3 \end{aligned} \tag{3}$$

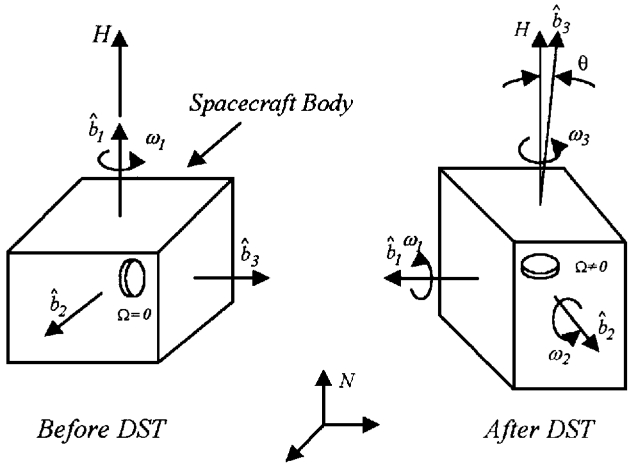

Fig. 1 Geometric description of the DST maneuver.

and the wheel dynamic equation with respect to the applied torque is derived as[9]

$$J_w(\dot{\omega}_3 + \dot{\Omega}) = u \tag{4}$$

where u is the applied torque. The generic DST maneuver is conducted with an external torque free condition $[L_1, L_2, L_3] = [0, 0, 0]$. In this case the total angular momentum in the inertial frame is conserved:

$$H^2 = |\hat{\boldsymbol{H}}|^2 = I_1^2\omega_1^2 + I_2^2\omega_2^2 + (I_3\omega_3 + J_w\Omega)^2 = \text{const} \tag{5}$$

Note that the total kinetic energy of the system is written as

$$\begin{aligned} E &= \tfrac{1}{2}I_1^s\omega_1^2 + \tfrac{1}{2}I_2^s\omega_2^2 + \tfrac{1}{2}I_3^s\omega_3^2 + \tfrac{1}{2}\left[I_1^*\omega_1^2 + I_2^*\omega_2^2 + J_w(\omega_3 + \Omega)^2\right] \\ &= \tfrac{1}{2}\left(I_1\omega_1^2 + I_2\omega_2^2 + I_3\omega_3^2\right) + \tfrac{1}{2}(1/J_w)h_3^2 + \omega_3 h_3 \end{aligned} \tag{6}$$

where $h_3 = J_w\Omega$ represents the relative angular momentum of the wheel with respect to spacecraft body axes. The time derivative of the total kinetic energy is a quantity of interest given in the form

$$\dot{E} = \Omega u \tag{7}$$

That is, the total energy is changed only by nonzero torque input $(u \neq 0)$. Furthermore, we introduce nutation angle as

$$\theta = \cos^{-1}\frac{I_3\omega_3 + J_w\Omega}{H} \tag{8}$$

The nutation angle is defined as the angle between the wheel axis and $\hat{\boldsymbol{b}}_3$ axis, the final spin axis after a DST maneuver. The nutation angle is used as a measure of the success of the DST maneuver. The main DST operational procedure is to spin up the wheel from initial speed to a certain desired level. The final nutation angle and transverse components of angular momentum during wheel spin up are key design parameters.

The stability analysis of a dual-spin spacecraft is slightly different from the DST maneuver. The dual-spin spacecraft stability[1–4] is analyzed mainly for a case in which the wheel speed is fixed with respect to the spacecraft body. On the other hand, the wheel speed changes dramatically in the DST maneuver. The core energy is a crucial parameter in the stability analysis of dual-spin spacecraft.[5–8] The core energy is the energy of a fictitious rigid body, which has the inertia property of a spacecraft body plus wheel but rotates like a single rigid body. The system core energy is expressed as[5–8]

$$E_c = \tfrac{1}{2}\left(I_1\omega_1^2 + I_2\omega_2^2 + I_3\omega_3^2\right) \tag{9}$$

Note that the total system energy and core energy are related as

$$E = E_c + \tfrac{1}{2}(1/J_w)h_3^2 + \omega_3 h_3 \tag{10}$$

and, consequently,

$$\dot{E} = \dot{E}_c + \dot{h}_3\omega_3 + \Omega u \tag{11}$$

The core energy decreases by a damper implemented in the spacecraft body even if the wheel spin up/down may contribute to adding energy.[5] Constant wheel speed maintained by overcoming frictional loss due to the damper is also attributed to an energy source. The nutation angle in Eq. (8), by combining Eqs. (5) and (9), can be expressed in terms of the core energy and magnitude of angular momentum:

$$\theta = \cos^{-1}\left[\left(\frac{I_1 h_3}{I_1 - I_3} \pm \frac{I_3}{I_1 - I_3}\sqrt{S}\right)\right] \tag{12}$$

where

$$S = h_3^2 - (I_1/I_3 - 1)\left[-h_3^2 - 2E_c I_1 + H^2 + \left(I_1 I_2 - I_2^2\right)\omega_2^2\right]$$

As a special case, if the spacecraft is axisymmetric with $I_1 = I_2 = I_t$ and $I_3 = I_s$, the nutation angle expression in Eq. (12) reduces to[7]

$$\theta = \cos^{-1}\left[\left(\frac{I_t}{I_t - I_s}\right)\frac{1}{H}(h_3 \pm \sqrt{S})\right] \tag{13}$$

where

$$S = 2E_c I_s[1 - (I_s/I_t)] - H^2(I_s/I_t)[1 - (I_s/I_t)] + (I_s/I_t)h_3^2$$

According to the energy sink approach for axisymmetric spacecraft, the core energy and nutational stability are closely related. The basic idea of minimum core energy by Hubert[5] and the symmetric axiom of Ross[7,8] investigated the core energy and the stability of nutational motion of axisymmetric dual-spin spacecraft. With constant Ω, as is the usual requirement of dual-spin spacecraft, Eq. (13) leads us to the following expression[7]:

$$\dot{\theta} = \frac{\dot{E}_c}{H\sin\theta}\left(\frac{I_s}{\sqrt{S}}\right) \tag{14}$$

This expression demonstrates the relationship between the core energy and nutation angle. That is, the core energy must decrease for the nutation angle to decrease. Unfortunately, a similar expression is not found from Eq. (12) for a generic unsymmetric spacecraft due to the presence of ω_2, Ω, and E_c. They are all time varying and coupled together, so that a simplified algebraic expression is not readily derived.

Even if not impossible, it is not easy to derive the expression for the time rate of change of the nutation angle of spacecraft with generic inertia properties. However, we elect to take the essential principle of energy sink analysis designing a feedback control law for our case. In other words, the core energy and associated nutational stability principle are applied to a spacecraft with unsymmetric geometry and time-varying wheel speed.

III. Feedback Control Law Design

In the preceding section, the fundamental principle of DST maneuver and motivation of the feedback control law design are discussed. In this section, a feedback control law is designed that achieves the DST maneuver by adjusting the wheel speed using the feedback control signal. The feedback control law approach is based on the core energy of spacecraft. The Lyapunov stability theory is applied to the control law design,[14] and a candidate Lyapunov function is selected as

$$\begin{aligned} U &= E_c + a_1\left(h_3 - h_3^f\right)^2 \\ &= \tfrac{1}{2}\left(I_1\omega_1^2 + I_2\omega_2^2 + I_3\omega_3^2\right) + a_1\left(h_3 - h_3^f\right)^2 \end{aligned} \tag{15}$$

where $a_1 > 0$ is a positive weighting factor and $h_3^f = \text{const}$ is the desired final angular momentum of the wheel. The Lyapunov function is a weighted combination of core energy and error energy of angular momentum. Note that it is not feasible to achieve the steady equilibrium point of the Lyapunov function prescribed as

$$(\omega_1, \omega_2, \omega_3, h_3) = \left(0, 0, 0, h_3^f\right) \tag{16}$$

In other words, the Lyapunov function does not converge to zero due to the inherent structure of Eq. (15). This is because the final wheel momentum h_3^f may not represent the total system angular momentum (H). Instead, it is usually smaller than H, and this results in a nonzero equilibrium condition of $(\omega_1, \omega_2, \omega_3) \neq (0, 0, 0)$ after the DST maneuver. This is also due to the angular momentum conservation principle given by Eq. (5).

At this point, we focus on deriving a control law from the Lyapunov function defined in Eq. (15). First, the time derivative of the Lyapunov function is taken as

$$\dot{U} = I_1\omega_1\dot{\omega}_1 + I_2\omega_2\dot{\omega}_2 + I_3\omega_3\dot{\omega}_3 + a_1\left(h_3 - h_3^f\right)\dot{h}_3 \tag{17}$$

Substitution of Eq. (3) with zero external torque into Eq. (17) yields

$$\dot{U} = \left[-\omega_3 + a_1\left(h_3 - h_3^f\right)\right]\dot{h}_3 \tag{18}$$

Note that the Lyapunov function time rate of change is divided into two parts,

$$\dot{U} = \dot{E}_c + \dot{E}_e \tag{19}$$

where $\dot{E}_c$ represents the core energy change rate and $\dot{E}_e$ corresponds to the error energy change rate. Each term is expressed as

$$\dot{E}_c = -\omega_3\dot{h}_3, \qquad \dot{E}_e = a_1\left(h_3 - h_3^f\right)\dot{h}_3 \tag{20}$$

As a sufficient condition for the Lyapunov stability, i.e., $\dot{U} < 0$, the wheel angular momentum is prescribed to satisfy a candidate stability condition given as

$$\dot{h}_3 = -a_2\left[-\omega_3 + a_1\left(h_3 - h_3^f\right)\right] \tag{21}$$

which in turn produces

$$\dot{U} = -a_2\left[-\omega_3 + a_1\left(h_3 - h_3^f\right)\right]^2 \tag{22}$$

where $a_2 > 0$ is another constant to be used as a design parameter. Thus, the time derivative of the Lyapunov function becomes negative on the condition that $-\omega_3 + a_1(h_3 - h_3^f) \neq 0$. This is true during most of the period considering $\omega_3 = 0$ and $h_3 = 0$ at the initial instant of maneuver. Another equation is derived by combining Eq. (4) and the third equation in Eq. (3) as

$$(I_3 - J_w)\dot{\omega}_3 + (I_2 - I_1)\omega_1\omega_2 + u = 0 \tag{23}$$

Equation (4) also can be rewritten as

$$\dot{h}_3 = u - J_w\dot{\omega}_3 = \frac{I_3 u}{I_3 - J_w} + \frac{J_w(I_2 - I_1)\omega_1\omega_2}{I_3 - J_w} \tag{24}$$

Furthermore, combination of Eqs. (21) and (24) yields

$$\frac{I_3 u}{I_3 - J_w} + \frac{J_w(I_2 - I_1)\omega_1\omega_2}{I_3 - J_w} = -a_2\left[-\omega_3 + a_1\left(h_3 - h_3^f\right)\right] \tag{25}$$

The final expression for the control input is obtained from Eq. (25) by solving for u as

$$u = -\frac{J_w(I_2 - I_1)\omega_1\omega_2}{I_3} - \frac{a_2(I_3 - J_w)}{I_3}\left[-\omega_3 + a_1\left(h_3 - h_3^f\right)\right] \tag{26}$$

The control input is, therefore, derived in a feedback control form. The feedback control law is divided into two parts: 1) gyroscopic coupling term and 2) feedback on the angular momentum error of the wheel. One disadvantage of the feedback control law is that we need all three angular velocity components and the wheel angular momentum information. However, the derived control law can be implemented without much difficulty in the sense that the body axis components of angular velocities are usually measurable. Also, the control law seemingly does not pose any constraint on the relative sizes of the spacecraft inertia properties (I_1, I_2, I_3).

The control law is expected to cause oscillatory behavior in motion once the wheel momentum reaches the desired level (h_3^f). This is because of the oscillation of $\dot{U}$ across a zero crossing line associated with the equilibrium point in Eq. (16). Therefore, the approach can be used only in the first stage of maneuver. During this stage, the wheel spins up until the equilibrium state is reached. After the equilibrium state, passive damping devices may be used for further decrease of nutation angle.

IV. Two-Stage Control Law Design

The control law designed as just described can be modified for performance improvement. As mentioned earlier, the majority of DST maneuvers are dominated by open-loop approaches. Once the wheel spins up by constant torque to a certain angular momentum level, the wheel speed is fixed to a constant value or set to a floating condition. The control law developed in this section combines a typical open-loop approach and a feedback control law based on the energy sink technique. The control law is derived in two separate stages.

Stage 1: Open-Loop Control with Constant Torque

In the first stage, constant torque is applied to the wheel in such a way that

$$J_w(\dot{\omega}_3 + \dot{\Omega}) = u = \text{const} \tag{27}$$

The torque is applied until the wheel speed reaches a predetermined value denoted as Ω_f. It is desired that the wheel absorb the system angular momentum with minimal nutation angle, that is, minimal transverse angular momentum components. This leads to the following expression for the final desired value of angular velocity of the body axis along which the wheel is aligned:

$$\omega_3^f = \frac{H - J_w\Omega_f}{I_3} \tag{28}$$

Equation (28) indicates that the wheel is required to absorb part of the angular momentum of the spacecraft and $\hat{\boldsymbol{b}}_3$ is the axis that is aligned with the total angular momentum vector.

Stage 2: Closed-Loop Control

Once the wheel spin up stage is completed, then the control law is switched to a closed-loop control. The residual nutation angle after the open-loop wheel acceleration is controlled by active feedback control. The closed-loop feedback control law is also based on the core energy theory.

For a different feedback control law derivation, the core energy definition is slightly modified to take into account the final equilibrium condition after the wheel spin up, prescribed as

$$(\omega_1, \omega_2, \omega_3, \Omega) = \left(0, 0, \omega_3^f, \Omega_f\right) \tag{29}$$

Therefore, a modified core energy called pseudocore energy is introduced as

$$E_c = \tfrac{1}{2}I_1\omega_1^2 + \tfrac{1}{2}I_2\omega_2^2 + \tfrac{1}{2}I_3\left(\omega_3 - \omega_3^f\right)^2 \tag{30}$$

The pseudocore energy has essentially the same characteristics as the original core energy in Eq. (9) except it is minimum at a different equilibrium point in Eq. (29). The time derivative of the pseudocore energy becomes

$$\dot{E}_c = I_1\omega_1\dot{\omega}_1 + I_2\omega_2\dot{\omega}_2 + I_3\left(\omega_3 - \omega_3^f\right)\dot{\omega}_3 \tag{31}$$

By taking a path similar to designing the previous control law, we arrive at

$$\dot{E}_c = -\dot{h}_3\left(\omega_3 - \omega_3^f\right) + (I_2 - I_1)\omega_1\omega_2\omega_3^f \tag{32}$$

For stability in the Lyapunov sense, once again we choose a candidate condition as

$$\dot{h}_3 = a_3\left(\omega_3 - \omega_3^f\right) \tag{33}$$

where $a_3 > 0$ is another design parameter to be selected. Therefore,

$$\dot{E}_c = -a_3\left(\omega_3 - \omega_3^f\right)^2 + (I_2 - I_1)\omega_1\omega_2\omega_3^f \tag{34}$$

Unfortunately, the stability is not guaranteed unconditionally but only if

$$a_3\left(\omega_3 - \omega_3^f\right)^2 > \left|(I_2 - I_1)\omega_1\omega_2\omega_3^f\right| \tag{35}$$

To complete the control law derivation, Eq. (24) is substituted into Eq. (33), finally producing

$$u = -\frac{J_w(I_2 - I_1)}{I_3}\omega_1\omega_2 + a_3\frac{I_3 - J_w}{I_3}\left(\omega_3 - \omega_3^f\right) \tag{36}$$

This control law is very similar to that of Eq. (26), except there is no direct feedback on the angular momentum of the wheel, which is compensated by the feedback on $\omega_3 - \omega_3^f$.

Even if the stability is not guaranteed, the control law in Eq. (36) decreases the core energy substantially. This is partially possible by taking a large value of a_3. For later use in the simulation study and stability check, a useful parameter stability index is introduced as

$$\text{SI} = -a_3\left(\omega_3 - \omega_3^f\right)^2 + (I_2 - I_1)\omega_1\omega_2\omega_3^f \tag{37}$$

Thus the stability in the Lyapunov sense depends on the sign of SI.

V. Application and Simulation

Simulation study is conducted for performance verification of the designed control laws. The example system taken for this goal is Koreasat at transfer orbit. The Koreasat is a three-axis stabilized pitch bias momentum spacecraft. The momentum wheel spins up from 0 to 6000 rpm for a DST maneuver at transfer orbit before final Earth capture. The inertia properties of Koreasat are given as $I_1 = 4958$, $I_2 = 3372$, $I_3 = 3989$ (in.-lb-s^2), and $J_w = 0.756$ (in.-lb-s^2). The spacecraft is spinning initially about the $\hat{\boldsymbol{b}}_1$ axis at 5 rpm. The desired angular momentum of the wheel is $h_3^f = 475$ (in.-lb-s), which corresponds to 6000 rpm of angular velocity.

For comparison purposes, simulation results of the conventional constant torque strategy (case 1) are presented together. Simulation results using the control law in Eq. (26) (case 2) are provided in Fig. 2. The Lyapunov function response presented in Fig. 3 reaches a steady-state value, as expected. The Lyapunov function response shows a similar trend with the nutation angle response. The results of two-stage control law (case 3) are shown in Fig. 4. The pseudocore

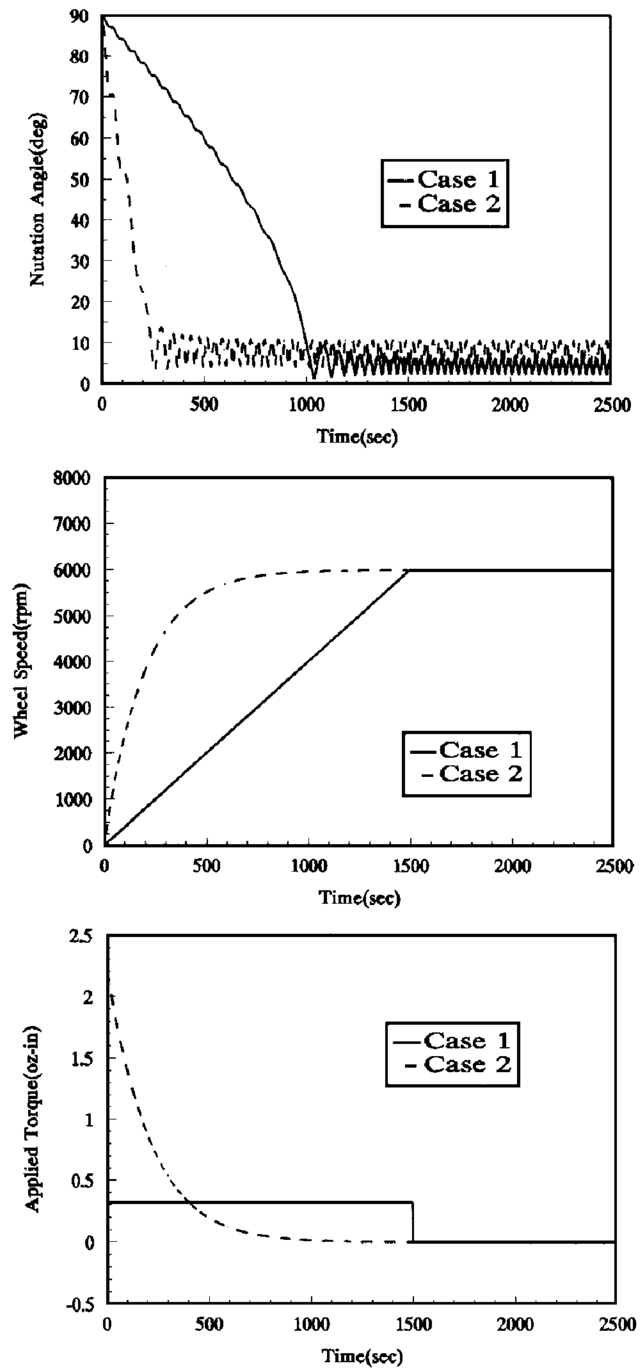

Fig. 2 Simulation results using direct feedback control law.

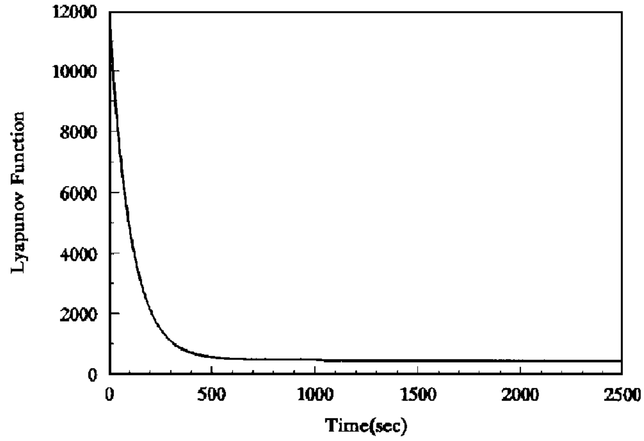

Fig. 3 Lyapunov function response for direct feedback control law.

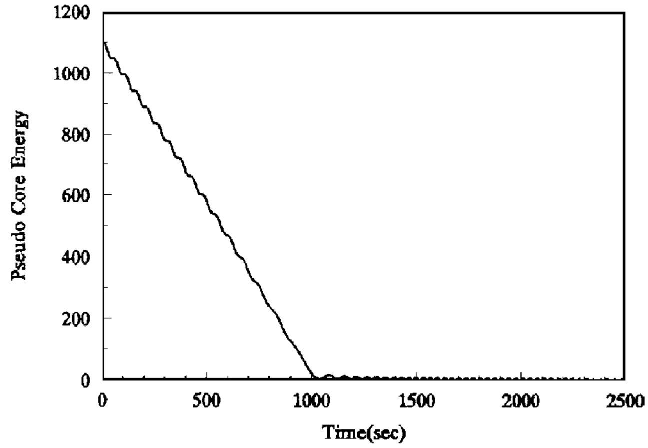

Fig. 5 Pseudocore energy response.

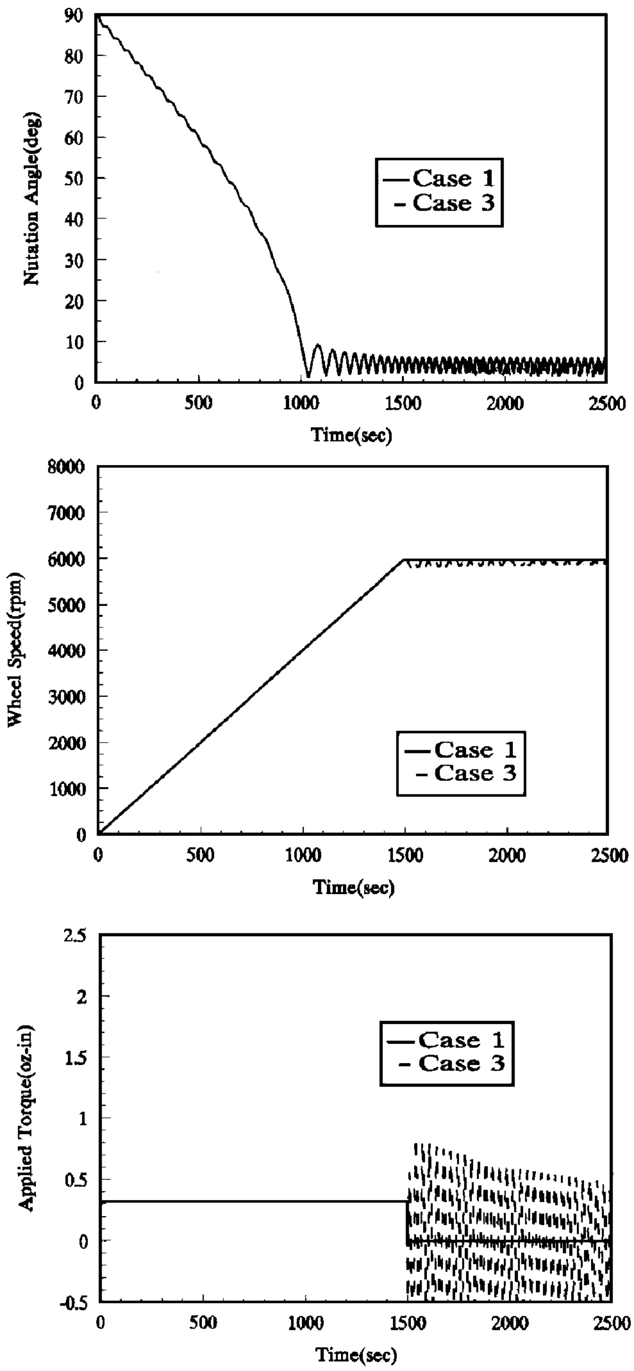

Fig. 4 Responses using the two-stage control law.

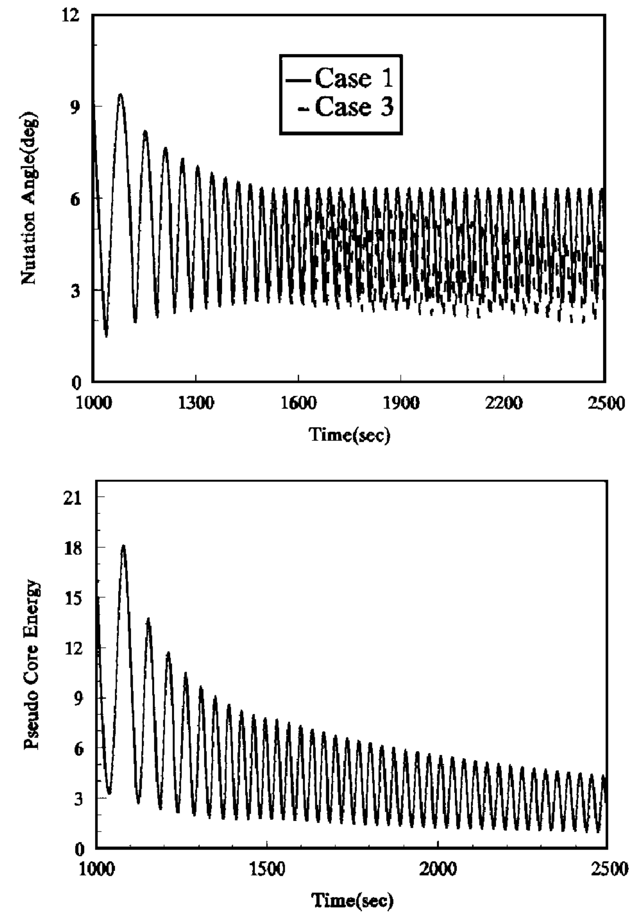

Fig. 6 Nutation angle and pseudocore energy responses in different time scales.

energy response is presented in Fig. 5. As expected, the pseudocore energy decreases from a large initial value toward zero, fluctuating gradually. The pseudoenergy is subject to the stability condition in Eq. (35), and asymptotic stability is not guaranteed. The pseudocore energy trend matches with the nutation angle response, again verifying the core energy and nutational stability relationship. In other words, the core energy and associated stability analysis can be applied to a nonaxisymmetric spacecraft for this particular problem. The nutation angle and pseudocore energy are plotted in different time scales in Fig. 6 for visualization purposes.

The stability index is plotted in Fig. 7. The sign of the stability index changes from negative to positive. It starts to oscillate around the zero crossing line after a certain maneuver time. This oscillatory behavior of the stability index is more dominant once the control switching occurs. At least during the simulation time, the stability

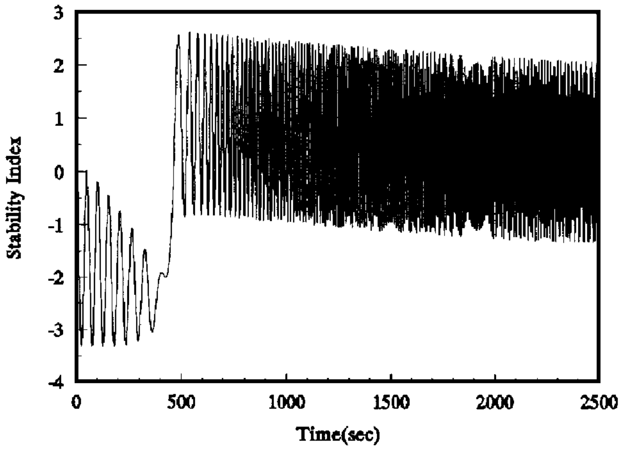

Fig. 7 Stability index responses for the two-stage control law.

index is shown to decrease gradually. This also matches with the nutation angle response.

From the simulation results, it is shown that the two-stage feedback control law, for a given set of design parameters, shows the best performance with smallest residual nutation angle. Obviously, different behaviors are expected, depending on the design parameters in the control law.

Both conventional open-loop strategy (case 1) and feedback control strategy (case 2) produce similar behavior of nutation angle at the steady state. However, it takes shorter maneuver time for the new feedback technique compared to the pure open-loop method. This is possible by selecting a set of free design parameters (a_1, a_2). The direct feedback control law (case 2) shows larger steady-state nutation angle than the pure open-loop (case 1) technique. This can also be resolved in part by selecting a different design parameter set (a_1, a_2). The direct feedback control law (case 2) has the advantage of almost constant wheel momentum, whereas the angular momentum of case 3 is slightly fluctuating at the steady state.

Note that in practical application we cannot eliminate completely the need for energy dissipation devices. The simulation result in Fig. 4 indicates that the nutation angle change rate decreases gradually. This is because of the oscillation of the stability index defined in Eq. (37), as is evident in Fig. 7. It is expected that the nutation angle may eventually reach an oscillating state about a certain lower limit. Because there is no guarantee that the nutational angle is asymptotically stable, the feedback control strategy needs to be augmented with passive damping devices from a practical point of view. The use of passive damping devices in DST attitude acquisition is well described in Ref. 5.

In the preceding simulation, the moment of inertia of the spacecraft satisfies $I_1 > I_2 > I_3$. In other words, the initial spin axis is the axis of maximum moment of inertia while the wheel is aligned along the minimum moment of inertia axis. In this nominal case, the nutational angle usually decreases from 90 deg by wheel acceleration in the positive direction. On the other hand, with the inertial properties satisfying $I_1 < I_2 < I_3$, the maneuver is characterized by a so-called inverted turn maneuver, as is discussed in Refs. 6 and 13. The inverted turn causes the nutational angle to increase with the positive wheel acceleration.[13] In Ref. 5, Hubert discusses using a passive device to overcome the inverted turn maneuver.

The feedback control law in Eq. (26) is again applied to a case of $I_1 < I_2 < I_3$ to examine the capability of the control law. The control law is directly activated from the initial spin state about the $\hat{\boldsymbol{b}}_1$ axis. Simulation results are presented in Fig. 8. The wheel speed increases in a negative direction from zero automatically to decrease the nutation angle. The feedback control law senses wheel acceleration direction autonomously, depending on the inertia properties and initial spin axis. However, the wheel is spinning in the direction opposite to the spacecraft main body. Examining additional simulation results, it turns out that the Lyapunov function in Eq. (15) continues to increase. This is due to the polarity of the final angular momentum (h_3^f) in Eq. (15). The polarity of h_3^f needs to be changed, depending on the final wheel spinning direction. The overall energy level of

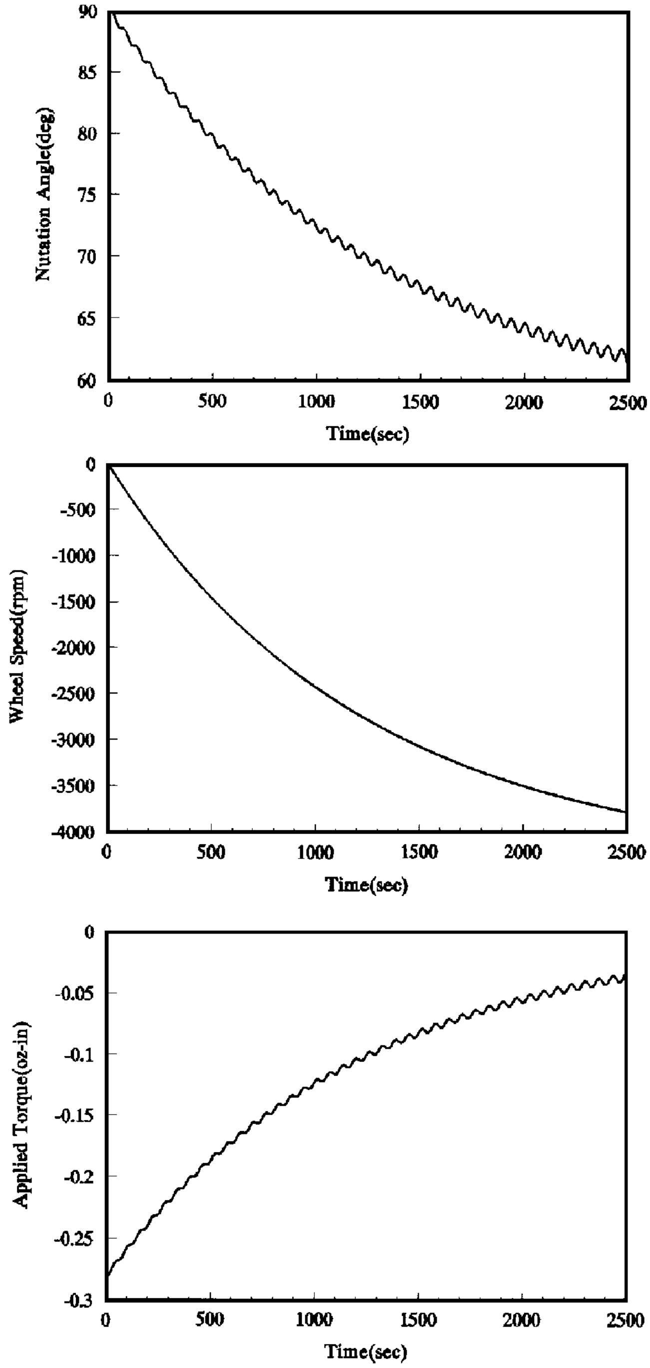

Fig. 8 Inverted DST maneuver simulation results.

the spacecraft also turns out to increase as well by this inverted turn maneuver. Despite the decrease in nutation angle and core energy, as shown in Fig. 8, the active control strategy still does not overcome the inverted turn maneuver successfully. Passive damping device is still needed in this case.[5]

VI. Conclusion

A new feedback control law for the DST maneuver of spacecraft was designed and demonstrated through a simulation study. The inherent nature of feedback control when it is compared with the open-loop approach is a main advantage of the proposed method. The active wheel speed control using body and wheel angular rate information was shown to successfully achieve the DST maneuver. The new technique turns out to have advantages of faster response time (case 1) and smaller residual nutation angle (case 3) compared with the pure open-loop technique. Also, the new technique provides freedom to choose design parameters determining feedback torque profiles, as well as resultant maneuver history. The inverted

DST maneuver simulation result, however, shows that the feedback control law does not achieve momentum transfer successfully. The wheel spins in the direction opposite to the spacecraft body while the nutation angle decreases. Further study may be needed to investigate technical issues that may arise in the practical implementation of the approach.

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