

Disturbance Accommodating Sliding Mode Controller for Spacecraft Attitude Maneuvers

Jongrae Kim*, Jinho Kim†, John L. Crassidis‡

In the absence of an external disturbance and uncertainty, sliding mode (variable structure) control is guaranteed to asymptotically stabilize a system, which is provided by using a correction control input calculated using a Lyapunov-type condition i.e., sliding mode existence condition. When bounded unmodeled external torques are added, the closed-loop system is no longer globally asymptotically stable since steady-state errors are present. The error can be minimized by increasing the correction control gain or decreasing the thickness of boundary layer of sliding mode control. But for limited actuator capability the maximum control gain and the minimum thickness of boundary layer being allowed may be restricted.

Disturbance accommodating control is a signal synthesis adaptive control. For a short time interval the disturbance is assumed to be modeled by a linear combination of previously selected basis functions. A disturbance accommodating observer can be used to identify unmeasurable internal and external disturbances. In this paper, sliding mode control is combined with disturbance accommodating control (i.e., Disturbance Accommodating Sliding Mode Control) in terms of modified Rodrigues parameters for a spacecraft attitude regulation and tracking maneuvers. The presented disturbance accommodating sliding mode control has the following advantages: 1) the design procedure is more effective than the traditional sliding surface stabilizing problem since steady-state errors are reduced, 2) the designed disturbance accommodating observer is linear, and 3) the robustness of sliding mode is guaranteed in the range of actuator capability. Simulation results are shown that use the disturbance accommodating sliding mode control to reduce steady-state errors in the case of applied external disturbances.

INTRODUCTION

Spacecraft attitude control for large-angle slewing maneuver poses a difficult problem, including the nonlinear characteristics of the governing equation, modeling

*Graduate Student, Dept. Mechanical Eng., The Catholic University of America, 73gim@pluto.ee.cua.edu

†Associate Professor, Dept. Aerospace Eng., Inha University, Incheon, Korea, jhkim@dragon.inha.ac.kr

‡Assistant Professor, Dept. Mechanical Eng., The Catholic University of America, jlc@pluto.ee.cua.edu

uncertainty and unexpected external disturbances. Sliding mode (variable structure) control provides robustness with respect to modeling errors and is an effective method for handling the nonlinear characteristics for attitude control. Variable structure control for multi-axial spacecraft attitude maneuvers was first presented by Dwyer and Rammirez.¹ In their paper, the sliding surface is defined by the Rodrigues parameters (gibbs vector). The Rodrigues parameters provide a minimal (i.e., three-dimensional) parameterization. However, the Rodrigues parameters have a singularity for 180 deg rotations. Vadali presented an optimal sliding manifold using error quaternions.² For large angle maneuvers, quaternion feedback was presented by Wie and Barba.³ A quaternion feedback regulator was also presented by Wie, Weiss and Arapostathis.⁴ Quaternions are nonsingular for any rotation, however, the use of quaternions requires an extra parameter that leads to a nonminimal parameterization. Crassidis and Markley developed a sliding mode controller for regulation and tracking problems of spacecraft attitude control based on the modified Rodrigues parameters.⁵ The advantages of using modified Rodrigues parameters include the following: 1) rotations up to 360 deg are possible, and 2) the parameters form a minimal parameterization.⁵ Therefore, in this paper, sliding mode control based on modified Rodrigues parameters is adopted. All of the above control laws are robust with respect to variations in the moment of inertia tensor on the order of 10 - 20 %.⁶

One of the drawbacks of sliding mode control is the chattering problem due to disturbance and modeling imprecision. For spacecraft attitude control, chattering may excite the higher frequencies of spacecraft and cause structural failure. Chattering can be settled by smoothing the control input using boundary layer or bandwidth-limited sliding mode control, which was presented by Dwyer and Kim⁷. However, a globally suitable boundary layer thickness cannot be easily determined. Moreover, for spacecraft attitude control it may be difficult to predict the external disturbances acting on body. When bounded unmodeled external torques are added, the closed-loop system is no longer globally asymptotically stable since a steady-state error is present. The error can be minimized by increasing the correction control gain or decreasing the thickness of boundary layer of sliding mode control. In this paper we derive this relation using a Lyapunov function. But for limited actuator capability the maximum correction control gain and the minimum thickness of boundary layer being allowed may be restricted. Though the steady-state errors are usually small, in a high-precision attitude pointing or tracking systems, these errors may not be tolerable for satisfying a mission requirement.

In this paper, we adopt disturbance accommodating control to minimize steady-state errors in sliding mode control. The disturbance accommodating control concept was first proposed by Johnson.^{9,10} External disturbances $w(t)$ are assumed to satisfy $d^{m+1}w(t)/dt^{m+1} = 0$ differential equation where the external disturbances are represented as m th-degree polynomials in time t with unknown coefficients.¹⁰ Design procedures and existence of the disturbance observer are presented in (Ref. 11, 12).

This is extended to internal disturbances arising from uncertain plant parameter variations in (Ref. 13). Some design examples are shown in (Ref. 14), and applied to the Hubble Telescope in (Ref. 15). A tutorial presentation of disturbance accommodating control is shown in (Ref. 16). In these papers, a disturbance accommodating observer is combined with a control method that provides linear behaviors in the responses of the systems. Advantages of using disturbance accommodating observer include the following: 1) it is linear, and 2) it also compensates the error due to modeling uncertainty.

Combining sliding mode control with a disturbance accommodating observer (i.e., Disturbance Accommodating Sliding Mode Control) was presented by Kim, and was applied to a robot manipulator for reducing the upper bound of bandwidth of sliding mode control.¹⁷ In this paper sliding mode control based on modified Rodrigues parameters is adopted for spacecraft attitude control. Also, a disturbance accommodating observer is combined with sliding mode control for reducing steady-state errors due to external disturbances. Simulation results that use the disturbance accommodating sliding mode control to reduce the steady-state error are shown for the case of regulation and tracking maneuvers.

The organization of this paper proceeds as follows. First, a brief summary of the kinematics and dynamics of a spacecraft is presented. Then, a brief overview of the sliding mode control based on modified Rodrigues parameters is shown. Next, a robust analysis of the sliding mode control with respect to external disturbances is accomplished using a Lyapunov function. A disturbance accommodating observer is derived for reducing the steady-state error. Also, sliding mode control and disturbance accommodating observer are combined. Finally, simulation results are shown for regulation and tracking of a spacecraft.

PROBLEM FORMULATION

In this section, a brief review of the kinematic equations of motion using modified Rodrigues parameters, the rigid body dynamics, and sliding mode control based on the kinematics is shown.

Attitude Kinematics and Dynamics

The modified Rodrigues parameters are defined by⁵

$$\mathbf{p} \equiv \hat{\mathbf{n}} \tan(\theta/4) \quad (1)$$

where \mathbf{p} is a 3×1 vector, $\hat{\mathbf{n}}$ is a unit vector corresponding to the axis of rotation and θ is the angle of rotation. The kinematic equations of spacecraft attitude motion described in modified Rodrigues parameters are derived by using the spacecraft's angular velocity ($\boldsymbol{\omega}$), given by⁵

$$\dot{\mathbf{p}} = 1/4 \left\{ (1 - \mathbf{p}^T \mathbf{p}) I_{3 \times 3} + 2 [\mathbf{p} \times] + 2 \mathbf{p} \mathbf{p}^T \right\} \boldsymbol{\omega} \quad (2)$$

where \mathbf{p}^T is the transpose of \mathbf{p} , $I_{3 \times 3}$ is a 3×3 identity matrix, and $[\mathbf{p} \times]$ is a 3×3 cross product matrix defined by

$$[\mathbf{p} \times] = \begin{bmatrix} 0 & -p_3 & p_2 \\ p_3 & 0 & -p_1 \\ -p_2 & p_1 & 0 \end{bmatrix} \quad (3)$$

The dynamic equation of motion for a rigid body with external disturbance (\mathbf{w}) is given by Euler's equation, defined by

$$\dot{\boldsymbol{\omega}} = J^{-1} [J\boldsymbol{\omega} \times] \boldsymbol{\omega} + J^{-1} \mathbf{u} + J^{-1} \mathbf{w} \quad (4)$$

where, J is the spacecraft's inertia (3×3) matrix, J^{-1} is the inverse matrix of J , and \mathbf{u} is the control input torque (3×1) vector.

Sliding Mode Control

In this paper it is assumed that measurements of both the spacecraft attitude and angular rate are available and the dynamics of actuator is neglected. The nonlinear model for spacecraft motion is summarized by⁵

$$\dot{\mathbf{p}} = F(\mathbf{p}) \boldsymbol{\omega} \quad (5)$$

$$\dot{\boldsymbol{\omega}} = \mathbf{f}(\boldsymbol{\omega}) + J^{-1} \mathbf{u} + J^{-1} \mathbf{w} \quad (6)$$

where

$$F(\mathbf{p}) \equiv 1/4 \{ (1 - \mathbf{p}^T \mathbf{p}) I_{3 \times 3} + 2[\mathbf{p} \times] + 2 \mathbf{p} \mathbf{p}^T \} \quad (7)$$

$$\mathbf{f}(\boldsymbol{\omega}) \equiv J^{-1} [J\boldsymbol{\omega} \times] \boldsymbol{\omega} \quad (8)$$

Sliding mode control introduces velocity vector fields directed toward the sliding surface or manifold ($\mathbf{s} = 0$) in its immediate vicinity, where \mathbf{s} is given by¹

$$\mathbf{s} \equiv \boldsymbol{\omega} - \mathbf{m}(\mathbf{p}) \quad (9)$$

The quantity $\mathbf{m}(\mathbf{p})$ is defined using a desired vector field from the kinematic equation, given by¹

$$\mathbf{m}(\mathbf{p}) = F^{-1}(\mathbf{p}) \mathbf{d}(\mathbf{p}) \quad (10)$$

where

$$F^{-1}(\mathbf{p}) = 4 (1 + \mathbf{p}^T \mathbf{p}) \{ (1 - \mathbf{p}^T \mathbf{p}) I_{3 \times 3} + 2[\mathbf{p} \times] + 2 \mathbf{p} \mathbf{p}^T \} \quad (11)$$

The quantity $\mathbf{d}(\mathbf{p})$ is formed by allowing a linear behavior in the sliding motion, given by⁵

$$\mathbf{d}(\mathbf{p}) = \Lambda (\mathbf{p} - \mathbf{p}_d) \quad (12)$$

where \mathbf{p}_d is the desired reference trajectory and Λ is a diagonal matrix with negative elements. The input by sliding mode control is divided into two parts. The first is the equivalent control \mathbf{u}_{eq} for satisfying the ideal sliding mode conditions (i.e., invariant

conditions). The second is the correction control \mathbf{u}_{cr} for satisfying the sliding mode existence conditions.¹ As a result, the control input is given by¹

$$\mathbf{u} = \mathbf{u}_{eq} + \mathbf{u}_{cr} \quad (13)$$

where

$$\mathbf{u}_{eq} = -J \left\{ \mathbf{f}(\boldsymbol{\omega}) - \frac{\partial \mathbf{m}}{\partial \mathbf{p}} F(\mathbf{p}) [\mathbf{m}(\mathbf{p}) + \mathbf{s}] \right\} \quad (14)$$

$$\mathbf{u}_{cr} = -JK \text{sat}(\mathbf{s}, \epsilon) \quad (15)$$

where K is a 3×3 positive definite diagonal matrix. The saturation function is used to minimize chattering in the control torques. The function is defined by

$$\text{sat}(s_i, \epsilon) \equiv \begin{cases} 1 & \text{if } s_i > \epsilon \\ s_i/\epsilon & \text{if } |s_i| \leq \epsilon \\ -1 & \text{if } s_i < -\epsilon \end{cases} \quad (16)$$

The detail descriptions of the quantities $\mathbf{m}(\mathbf{p})$ and $\partial \mathbf{m} / \partial \mathbf{p}$ for the regulation and the tracking problems can be found in (Ref. 5).

CONTROL DESIGN

In this section a robust analysis of the sliding mode control with respect to a external disturbance is accomplished using a Lyapunov function. A disturbance accommodating observer is also derived for reducing the steady-state error. Finally sliding mode control and disturbance accommodating observer are combined.

Robust Analysis of Sliding Mode Control

We use the following candidate Lyapunov function V to study global stability of the motion by sliding mode control.⁸

$$V = \frac{1}{2} \mathbf{s}^T J \mathbf{s} \quad (17)$$

Define an error torque $\Delta \mathbf{w}$ using an estimated external disturbance $\hat{\mathbf{w}}$ and the actual external disturbance through⁸

$$\Delta \mathbf{w} = \hat{\mathbf{w}} - \mathbf{w} \quad (18)$$

The first time derivative of the candidate Lyapunov function with the control input reduces to⁸

$$\dot{V} = -\mathbf{s}^T JK \text{sat}(\mathbf{s}, \epsilon) - \mathbf{s}^T \Delta \mathbf{w} \quad (19)$$

Note that in the absence of an external disturbance estimation error, this system is guaranteed to be globally asymptotically stable. If bounded unmodeled disturbances are added, but not compensated for in the control law, the system is no longer asymptotically stable. If K is large enough so that $\mathbf{s}^T JK \text{sat}(\mathbf{s}, \epsilon)$ is larger than $\mathbf{s}^T \Delta \mathbf{w}$, then

\dot{V} is guaranteed to be negative. Substituting the control torque into the first time derivative of sliding function, the following dynamics is obtained⁸

$$\dot{\mathbf{s}} = -K \text{sat}(\mathbf{s}, \epsilon) - J^{-1} \Delta \mathbf{w} \quad (20)$$

We assume that the thickness of boundary layer ϵ is sufficiently small and the correction control gain K is sufficiently large to keep the time derivative of Lyapunov function negative-definite with bounded external disturbances in the region of the outer boundary layer. In the boundary layer the dynamics of sliding function is given by

$$\dot{\mathbf{s}} = -\frac{K}{\epsilon} \mathbf{s} - J^{-1} \Delta \mathbf{w} \quad (21)$$

If the estimation error of external disturbance settles to a value and the sliding function \mathbf{s} must settle to a finite constant steady-state value \mathbf{s}_{ss} . Setting the derivative in the dynamics of sliding function to zero we obtain⁸

$$0 = -\frac{K}{\epsilon} \mathbf{s}_{ss} - J^{-1} \Delta \mathbf{w} \quad (22)$$

Therefore the steady-state value of sliding function (i.e., tracking error) will converge to the following finite offset⁸

$$\mathbf{s}_{ss} = -\frac{\epsilon}{K} J^{-1} \Delta \mathbf{w} \quad (23)$$

The tracking error will not converge to zero but to a finite offset. This offset can be reduced to fall within acceptable limits by decreasing the boundary layer thickness ϵ or increasing the correction control gain K . However, decreasing the boundary layer or increasing the correction control gain will limit the error recovery performance by saturating the actuator or will cause high frequency chattering in the actuator.⁸ For high-precision attitude tracking, this small error offset or the high gain may not be acceptable. The steady-state error can also be reduced by making $\Delta \mathbf{w}$ smaller.

Disturbance Accommodating Observer

The uncertainty associated with some internal and external disturbances $\mathbf{w}(t)$ is represented by a semideterministic waveform-model description of the generalized spline-function type, given by¹⁶

$$\mathbf{w}(t) = \mathbf{c}_1 f_1(t) + \mathbf{c}_2 f_2(t) + \cdots + \mathbf{c}_m f_m(t) \quad (24)$$

where the basis functions $f_1(t)$, $f_2(t)$, \cdots $f_m(t)$ are completely known and the constant weighting coefficient vectors \mathbf{c}_1 , \mathbf{c}_2 , \cdots \mathbf{c}_m are totally unknown and may jump in value from time to time. Without loss of generality, it is further assumed that the basis functions $f_i(t)$ satisfy a linear differential equation. As a consequence, there exists a linear dynamical "state model" representation as follows:¹⁶

$$\mathbf{w}(t) = H(t) \mathbf{z} \quad (25)$$

$$\dot{\mathbf{z}} = D(t)\mathbf{z} + \boldsymbol{\sigma}(t) \quad (26)$$

where $H(t)$, $D(t)$ are completely known and $\boldsymbol{\sigma}(t)$ is a vector of impulse sequences representing jumps in the \mathbf{c}_i which are sparse but otherwise totally unknown. The waveform and state models have been successfully used to represent plant model errors associated with the following items:¹⁶

1. coulomb and other complex forms of nonlinear damping
2. uncertain external input disturbances
3. plant parameter model errors
4. coupling effects in reduced-order state models

The basis functions can be chosen as power series in time t or as orthogonal polynomials commonly used in approximation theory.¹⁶ The design procedure and the existence problem of the appropriate observer with the stabilizing gain was shown in (Ref. 12).

Disturbance Accommodating Sliding Mode Control

In this paper we divide the control input into the equivalent control input \mathbf{u}_{eq} and the correction control input \mathbf{u}_{cr} of the sliding mode control and the disturbance accommodating control input \mathbf{u}_{dac} for canceling the effects of external disturbances.^{16,17}

$$\mathbf{u} = \mathbf{u}_{eq} + \mathbf{u}_{cr} + \mathbf{u}_{dac} \quad (27)$$

After applying the control input to the dynamics of the sliding function, the dynamics and the disturbance model can be written in the following state-space form:^{16,17}

$$\dot{\mathbf{s}} = J^{-1}\mathbf{u}_{cr} + J^{-1}\mathbf{u}_{dac} + J^{-1}\mathbf{w} \quad (28)$$

$$\dot{\mathbf{z}} = D(t)\mathbf{z} + \boldsymbol{\sigma}(t) \quad (29)$$

$$\mathbf{w} = H(t)\mathbf{z} \quad (30)$$

The appropriate disturbance accommodating observer is given by¹²

$$\dot{\hat{\mathbf{z}}} = D(t)\hat{\mathbf{z}} - K_0(\mathbf{z} - \hat{\mathbf{z}}) \quad (31)$$

$$\dot{\hat{\mathbf{w}}} = H(t)\hat{\mathbf{z}} \quad (32)$$

where, K_0 is the observer gain (9×9) matrix which provides sufficient time constants in the observer. We adopt the three basis functions as 1, t , t^2 for each body axis (i.e., $i = 1, 2, 3$).

$$w_i(t) = c_1 + c_2t + c_3t^2 \quad (33)$$

We assume that the time derivative of the jerk of external disturbance is zero (i.e., $d^3w_i(t)/dt^3 = 0$), so that H_i , D_i are given by

$$H_i = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \quad (34)$$

$$D_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \quad (35)$$

All the matrices in the observer are constant, however, the observer in Eq. (31) cannot be directly implemented due to the unmeasurable state \mathbf{z} . Define a new state variable \mathbf{Q} as follows:¹⁷

$$\mathbf{Q} = \hat{\mathbf{z}} - K_1 \mathbf{s} \quad (36)$$

where K_1 is a gain matrix (9×3). The gain K_1 can be tuned to satisfy the following condition:¹⁷

$$K_0 + K_1 H = 0 \quad (37)$$

Finally, the modified observer composed by the measurable or known states is derived as follows:¹⁸

$$\dot{\mathbf{Q}} = (D + K_0)\mathbf{Q} + (D + K_0)K_1 \mathbf{s} - K_1 J^{-1}(\mathbf{u}_{cr} + \mathbf{u}_{dac}) \quad (38)$$

where the initial condition is given by $\mathbf{Q}(0) = -K_1 \mathbf{s}(0)$. Then, the estimation error dynamics becomes¹⁸

$$\Delta \dot{\mathbf{Q}} - (D + K_0) \Delta \mathbf{Q} = -\sigma(t) \quad (39)$$

where

$$\Delta \mathbf{Q} = (\hat{\mathbf{z}} - K_1 \mathbf{s}) - (\mathbf{z} - K_1 \mathbf{s}) \quad (40)$$

If the gain K_0 is large enough so that the error dynamics is stable and converges fast, then the tracking error offset is reduced. The designed observer is linear and it can be easily implemented in digital software. One of drawbacks of the observer is that the sensor noise is amplified by the gain at the output of the observer. In this case we cannot use the reduced observer form, and have to implement a observer to estimate the state \mathbf{s} .

A brief description of the control and system is shown in Figure 1. The estimated states $\hat{\mathbf{z}}$, $\hat{\mathbf{w}}$ and \mathbf{u}_{dac} are calculated by the following relation:^{16,17}

$$\hat{\mathbf{z}} = \mathbf{Q} + K_1 \mathbf{s} \quad (41)$$

$$\hat{\mathbf{w}} = H \hat{\mathbf{z}} \quad (42)$$

$$\mathbf{u}_{dac} = -\hat{\mathbf{w}} \quad (43)$$

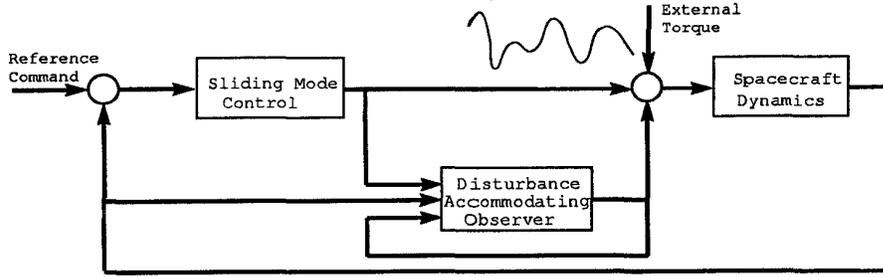


Figure 1 System Block Diagram

SIMULATION

The inertia matrix of the simulated spacecraft is given by⁵

$$J = \text{diag} [114 \quad 86 \quad 87] [kg \ m^2] \quad (44)$$

The initial conditions for the angular velocity are set to zero. The boundary layer thickness ϵ in the saturation controller is set to 0.01.⁵ Also, the control torques are limited to 1.0 N-m.⁵ The simulations are performed by Runge-Kutta 5 method in simulink in MATLAB with a maximum step size of 1 sec, minimum step size of 0.0001 sec and a tolerance 1.0×10^{-6} . The external disturbances applied to each body axis are set to $0.3 \sin(t/10)$ N-m. The observer gain K_{0_i} for each body axis (i.e., $i = 1, 2, 3$) is calculated using a pole-placement method as the following:

$$K_{0_i} = \begin{bmatrix} -30.0 & 0 & 0 \\ -300.0 & 0 & 0 \\ -1000.0 & 0 & 0 \end{bmatrix} \quad (45)$$

Simulation cases for the regulation and tracking problems are given by

1. Case A: Sliding Mode Control without the external disturbances
2. Case B: Sliding Mode Control with the external disturbances
3. Case C: Disturbance Accommodating Sliding Mode Control with the external disturbances

Regulation

The initial conditions for the modified Rodrigues parameters are given by

$$\mathbf{p}(0) = [-0.1 \quad 0.5 \quad 1.0]^T \quad (46)$$

The rotation for the initial conditions is approximately 206 deg. The diagonal elements of the correction control gain K are all set to 0.0015 and the constant λ

(the diagonal term of Λ) is set to -0.015 sec^{-1} . The sliding function trajectories of modified Rodrigues parameters for each case are shown in Figure 2. As shown in Figure 2, the trajectory of Case B oscillates in the boundary layer. In Case C, when disturbance accommodating sliding mode control applied the trajectory is almost the same as the one of Case A. The estimation errors, Δw , are shown in Figure 3. The maximum estimation errors for each body axes are smaller than 1.7 % with respect to the maximum external torques.

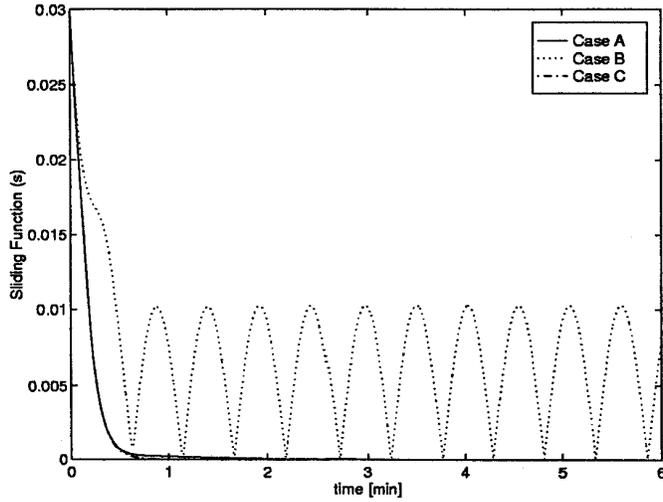


Figure 2 Regulation: Sliding Function Trajectories

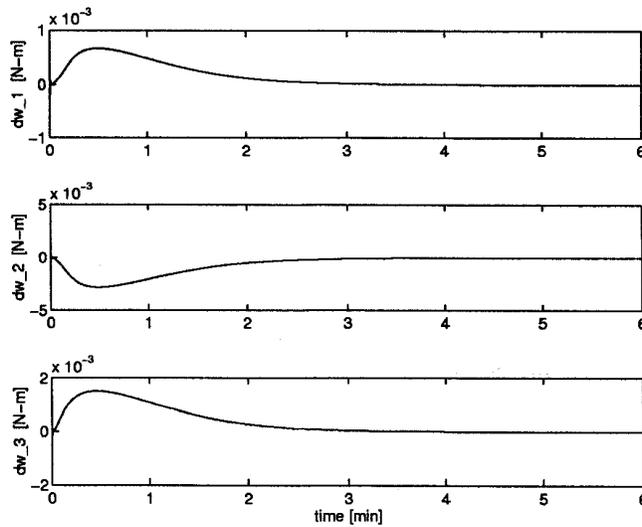


Figure 3 Regulation: Estimation Errors Δw

Tracking

The initial conditions for the angular velocity and the modified Rodrigues parameters are set to zero. The diagonal elements of the correction control gain K are set to 0.03 and the constant λ is set to -0.3 sec^{-1} . The desired trajectories of modified Rodrigues parameter \mathbf{p}_d are given by

$$p_{d1} = 0.05 \sin(0.005t) \quad (47)$$

$$p_{d2} = 0.05 \sin(0.006t) \quad (48)$$

$$p_{d3} = -0.05 \sin(0.007t) \quad (49)$$

The sliding function trajectories for each case are shown in Figure 4. As shown in Figure 4, the trajectory of Case B oscillates up and down through the trajectory of Case A. In Case C, when disturbance accommodating sliding mode control applied the trajectory is almost the same as the one of Case A. The estimation errors, $\Delta \mathbf{w}$, are shown in Figure 5. The maximum estimation errors for each body axes are smaller than 17 % with respect to the maximum external torques.

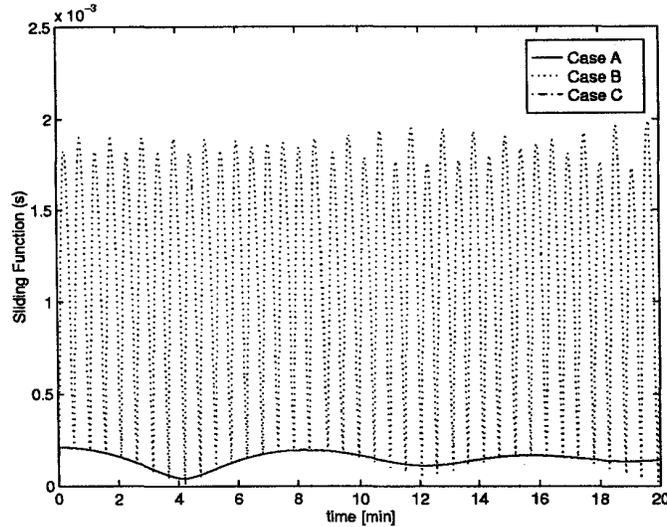


Figure 4 Tracking: Sliding Function Trajectories

CONCLUSION

A method for compensating the steady-state error of sliding mode control due to external disturbance was presented and applied to spacecraft attitude maneuvers. The presented disturbance accommodating sliding mode control include the following advantages: 1) the design procedure is more effective than the traditional sliding surface stabilizing problem since steady-state errors are reduced, 2) the designed disturbance accommodating observer is linear allowing the use of many design and

analysis methods for linear systems, and 3) the robustness of sliding mode is guaranteed in the range of actuator capability. Simulation results indicate that the new algorithm was able to reduce the upper bound of the steady-state error.

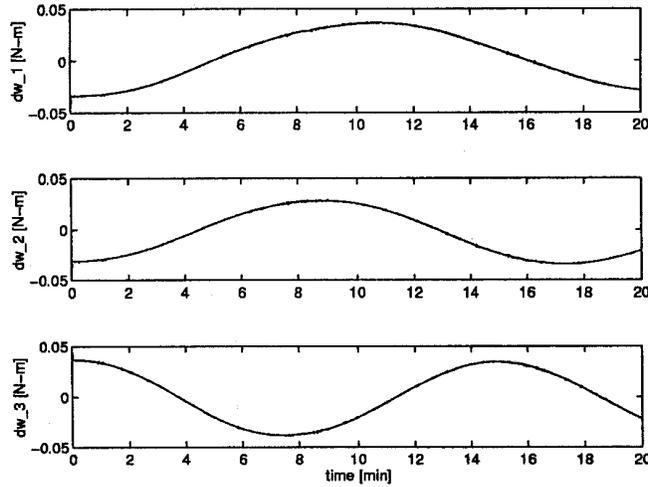


Figure 5 Tracking: Estimation Errors Δw

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