Quasi-Continuous Higher-Order Sliding Mode Controller Designs for Spacecraft Attitude Tracking Manoeuvres

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***Abstract*— This paper studies high-order sliding mode control laws to deal with some spacecraft attitude tracking problems. Second and third order quasi-continuous sliding control are applied to quaternion-based spacecraft attitude tracking manoeuvres. A class of linear sliding manifolds is selected as a function of angular velocities and quaternion errors. The second method of Lyapunov theory is used to show that tracking is achieved globally. An example of multiaxial attitude tracking manoeuvres is presented and simulation results are included to verify and compare the usefulness of the various controllers.**

I. Introduction

In general spacecraft motion is governed by the so-called kinematics equations and dynamics equations [1]. These mathematical descriptions are highly nonlinear and thus linear feedback control techniques are not suitable for the global controller design.

First-order sliding mode control has been considered as a useful scheme for spacecraft attitude control. Vadeli [2] designed a variable structure attitude control law based on quaternion kinematics. A similar approach was later proposed in [3] where sliding mode controller was designed for spacecraft tracking problems. This was illustrated by an example of multiaxis attitude tracking manoeuvres. An adaptation of the sliding mode control technique was derived and applied to a quaternion-based spacecraft attitude tracking manoeuvres. This modified version presented in [4] is the smoothing model-reference sliding mode control (SMRSMC). This technique improves the transient response and reduces the chatter phenomenon. In [5] the (additive) quaternion-based tracking of spacecraft manoeuvres used sliding mode control in the sense of optimal control. McDuffie and Shtessel [6] designed a de-coupled sliding mode controller and observer for spacecraft attitude control.

From the previous literature we conclude that sliding mode control can be used for quaternion-based spacecraft attitude tracking manoeuvres. Floquet [7] presented the stabilization of the angular velocity of rigid body via first-order and second-order sliding mode controllers but it has not been applied to spacecraft tracking problems. Higher-order sliding mode control has desired properties, such as robustness, similar to sliding mode control. It also may reduce chattering and provides better accuracy than first order sliding. Hence we will study spacecraft attitude tracking manoeuvres using higher-order sliding mode control.

This paper is organized as follows. Section II presents the kinematics and dynamic equations of a rigid spacecraft. In Section III the sliding manifold and first-order sliding mode control are presented for attitude tracking manoeuvres. In Section IV the sliding manifold and the second-order quasi-continuous controller [8] are presented. A first-order differentiator [9] is applied to estimate the time derivative of the sliding vector. Section V presents the design of third-order quasi-continuous controller. We add a precompensator (first-order lag) to the spacecraft model description to smooth the control signal, and use a second-order differentiator [7] to estimate the first and second time derivatives of the sliding vector. A numerical example of the multiaxial attitude tracking problem [4] is illustrated in Section VI to verify the usefulness the third-order quasi continuous controller. Section VII is the conclusion.

II. Spacecraft Model Description

We consider the general case of a rigid spacecraft rotating under the influence of body-fixed torquing devices. According to [10], the kinematics equation and the dynamics equation are given by

$$\begin{aligned} \dot{q} &= \frac{1}{2}T(Q)\omega \\ \dot{q_4} &= -\frac{1}{2}q^T\omega \end{aligned} \tag{1}$$

and

$$J\dot{\omega} = -[\omega\times]J\omega + u + d \tag{2}$$

where $Q = [q^T \quad q_4]^T$ is the quaternion with $q = [q_1 \quad q_2 \quad q_3]^T$, $\omega = [\omega_1 \quad \omega_2 \quad \omega_3]^T$ is the angular velocity vector, and

$$T(Q) = (q_4 I_3 + [q\times]) \tag{3}$$

where I_3 is a 3×3 identity matrix and $[q\times]$ is a skew-symmetric matrix expressed by

$$[q\times] = \begin{bmatrix} 0 & -q_3 & q_2 \\ q_3 & 0 & -q_1 \\ -q_2 & q_1 & 0 \end{bmatrix} \tag{4}$$

In (2) $u = [u_1 \quad u_2 \quad u_3]^T$ is the control vector, $d = [d_1 \quad d_2 \quad d_3]^T$ represents bounded disturbances, and J is the inertia matrix. The kinematic equation (1) can be rewritten

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in a more compact form as [11]

$$\dot{Q} = \frac{1}{2}E(Q)\omega \quad (5)$$

where

$$E(Q) = \begin{bmatrix} T(Q) \\ -q^T \end{bmatrix} \quad (6)$$

Note that the elements of Q are restricted by

$$\|Q\| = 1 \quad \text{or} \quad q_1^2 + q_2^2 + q_3^2 + q_4^2 = 1 \quad (7)$$

III. Attitude Tracking by First-Order Sliding Controller

We mention briefly the first order sliding approach [4] so that we can compare our improved results later. The development of their controller is not presented here (for lack of space). The sliding vector is

$$s = \omega_e + Kq_e \quad (8)$$

and the sliding controller is

$$u = [\omega\times]J_0\omega + J_0\dot{\upsilon}_d - J_0K[\frac{1}{2}T(Q)\omega - \dot{q}_d] + \tau \quad (9)$$

where $\tau = [\tau_1 \quad \tau_2 \quad \tau_3]^T$ and $\tau_i = -g_i\text{sign}(s_i)$. They also proposed an improved more complicated SMRSMC controller that improves the reaching phase transient dynamics and avoids chattering.

IV. Attitude Tracking by Second-Order Quasi-Continuous Controller

The quasi-continuous controller presented in [8] is a class of higher-order sliding mode controller. Here the second-order quasi-continuous controller (QC2S) is developed to achieve robust attitude tracking.

To avoid the singularity of $T(Q)$ that will occur at $q_4 = 0$, let the attitude of the spacecraft be restricted in the workspace W [4] defined by

$$W = \{Q | Q = [q^T \quad q_4]^T, \|q\| \le \beta < 1, q_4 \ge \sqrt{1-\beta^2} > 0\} \quad (10)$$

A. Sliding manifold

A class of linear sliding vectors is chosen as follows:

$$s = \omega_e + Kq_e \quad (11)$$

where K is a 3×3 symmetric positive-definition constant matrix, $\omega_e = \omega - \upsilon_d$, $q_e = q - q_d$, and $\upsilon_d = 2T^{-1}(Q)\dot{q}_d$. In [4] a similar sliding manifold was introduced to apply to the sliding mode controller for the spacecraft attitude tracking manoeuvres. It was proved that, by choosing Lyapunov function $V = \frac{1}{2}q_e^T Kq_e$ with positive definite K, the tracking error q_e converges to zero.

B. Control law

In this section we study QC2S and the first-order real-time differentiator for spacecraft attitude tracking manoeuvres. In order to use the second-order quasi-continuous controller we need to know the time derivative of the sliding vector ($\dot{s}$). Because it is very complicated to find $\dot{s}$ theoretically for this nonlinear system, we use the first-order Levant differentiator [9] for the estimation of $\dot{s}$. A first-order real-time differentiator has the form

$$\begin{aligned} \dot{z}_0 &= -\lambda_1|z_0 - s|^{1/2}\text{sign}(z_0 - s) + z_1 \\ \dot{z}_1 &= -\lambda_2\text{sign}(z_0 - s) \end{aligned} \quad (12)$$

where z_0, z_1 are real-time estimations of s and $\dot{s}$ respectively. The second-order quasi-continuous SM controller [8] is designed as

$$u = -\alpha\frac{z_1 + |z_0|^{1/2}\text{sign}z_0}{|\dot{z}_1| + |z_0|^{1/2}}. \quad (13)$$

Now we design the second-order quasi-continuous controller such that the reaching and sliding conditions are satisfied. We show that tracking is achieved globally (by using the Lyapunov second method) following the approach of [4]. Since J is symmetric and positive definite, the candidate Lyapunov function is chosen as

$$V_s = \frac{1}{2}s^T Js \ge 0 \quad (14)$$

and $V_s = 0$ only when $s = 0$. Taking the first derivative of V_s and using (1), (2) and (11), we have

$$\begin{aligned} \dot{V}_s &= s^T\{-[\omega\times]J\omega + u + d - J\dot{\upsilon}_d \\ &\quad +JK(\dot{q} - \dot{q}_d) + \dot{J}s\}. \end{aligned} \quad (15)$$

Let $J = J_0 + \Delta J$ where J_0 and ΔJ denote the nominal and uncertain part of the inertia matrix. Using (1) then (15) becomes

$$\begin{aligned} \dot{V}_s &= s^T\{-[\omega\times]\Delta J\omega - \Delta J\dot{\upsilon}_d + \Delta JK[\frac{1}{2}T(Q)\omega \\ &\quad -\dot{q}_d] + u + d + \dot{J}s - [\omega\times]J_0\omega - J_0\dot{\upsilon}_d \\ &\quad +J_0K[\frac{1}{2}T(Q)\omega - \dot{q}_d]\}. \end{aligned} \quad (16)$$

Suppose that the external disturbances d and uncertain parameters ΔJ and $\dot{J}$ are all bounded and that these bounds are known. Let $\delta = \{-[\omega\times]\Delta J\omega - \Delta J\dot{\upsilon}_d + \Delta JK[\frac{1}{2}T(Q)\omega - \dot{q}_d] + d + \dot{J}s\}$ and $\gamma = \{-[\omega\times]J_0\omega - J_0\dot{\upsilon}_d + J_0K[\frac{1}{2}T(Q)\omega - \dot{q}_d]\}$. Then (16) becomes

$$\begin{aligned} \dot{V}_s &= s^T[\delta + u + \gamma] \\ &= \sum_{i=1}^{3} s_i(\delta_i + u_i + \gamma_i). \end{aligned} \quad (17)$$

By setting the controller as

$$u = -k\frac{\dot{s} + |s|^{1/2}\text{sign}s}{|\dot{s}| + |s|^{1/2}} \quad (18)$$

and letting $\Psi_i = \delta_i + \gamma_i$, we have

$$\begin{aligned} \dot{V}_s &= \sum_{i=1}^{3} s_i \left[\Psi_i - k_i \left(\frac{\dot{s}_i + |s_i|^{1/2}\mathrm{sgn}(s_i)}{|\dot{s}_i| + |s_i|^{1/2}} \right) \right] \\ &= \sum_{i=1}^{3} s_i \Psi_i - \sum_{i=1}^{3} k_i s_i \mathrm{sgn}(s_i) \left(\frac{\dot{s}_i \mathrm{sgn}(s_i) + |s_i|^{1/2}}{|\dot{s}_i| + |s_i|^{1/2}} \right) \\ &= \sum_{i=1}^{3} |s_i| k_i \left[\frac{\Psi_i \mathrm{sgn}(s_i)}{k_i} - \frac{\dot{s}_i \mathrm{sgn}(s_i) + |s_i|^{1/2}}{|\dot{s}_i| + |s_i|^{1/2}} \right] \quad (19) \end{aligned}$$

To guarantee the reaching and sliding on the manifold, we require

$$\frac{\dot{s}_i \mathrm{sgn}(s_i) + |s_i|^{1/2}}{|\dot{s}_i| + |s_i|^{1/2}} \geq \frac{\Psi_i \mathrm{sgn}(s_i)}{k_i} \quad (20)$$

Since $\frac{\dot{s}_i \mathrm{sgn}(s_i) + |s_i|^{1/2}}{|\dot{s}_i| + |s_i|^{1/2}} \leq 1$, (20) can be written as

$$k_i \geq \Psi_i \mathrm{sgn}(s_i). \quad (21)$$

The upper bound of $|\Psi_i|$ can be found and denoted as

$$|\Psi_i| < \Psi_i^{max}(Q, \omega, q_d, \dot{q}_d, \ddot{q}_d). \quad (22)$$

Obviously, if we choose the gain k_i as $k_i \geq \Psi_i^{max}(Q, \omega, q_d, \dot{q}_d, \ddot{q}_d)$ then $\dot{V}_s < 0$. This guarantees the reaching and sliding on the manifold. Note that the bounds (22) are functions of the states so simulation studies are needed to assess their magnitudes and Lyapunov function V_s exists when condition (21) is satisfied.

V. Third-Order Quasi-Continuous Controller

We next consider the third order quasi-continuous (QC3S) controller to achieve to the spacecraft attitude tracking manoeuvres. Because it is a third-order sliding mode controller which normally provides very accurate outputs, we expect higher accuracy of the tracking results. Moreover, we add a first-order lag to the spacecraft model description to smooth the control signals.

Because it is very complicated to find $\dot{s}$ and $\ddot{s}$ from this system, we use the second order Levant differentiator [9] for the estimations of $\dot{s}$ and $\ddot{s}$.

A second-order real-time differentiator [9] is

$$\begin{aligned} \dot{z}_0 &= v_0 \\ v_0 &= -\lambda_1 |z_0 - s|^{2/3} \mathrm{sign}(z_0 - s) + z_1 \\ \dot{z}_1 &= v_1 \\ v_1 &= -\lambda_2 |z_1 - v_0|^{1/2} \mathrm{sign}(z_1 - v_0) + z_2 \\ \dot{z}_2 &= -\lambda_3 \mathrm{sign}(z_2 - v_1) \quad (23) \end{aligned}$$

where z_0, z_1 and z_2 are real-time estimations of s, $\dot{s}$ and $\ddot{s}$ respectively.

The third-order quasi continuous SM controller is

$$u = -\alpha \left[\frac{z_2 + 2(|z_1| + |z_0|^{2/3})^{-1/2}(z_1 + |z_0|^{2/3}\mathrm{sign}(z_0))}{|z_2| + 2(|z_1| + |z_0|^{2/3})^{1/2}} \right] \quad (24)$$

To guarantee the reaching and sliding on the manifold we select the Lyapunov function $V_s = \frac{1}{2} s^T J s$ and follow the same process as for the proof of QC2S. We select the control law as

$$u = -k \left[\frac{\ddot{s} + 2(|\dot{s}| + |s|^{2/3})^{-1/2}(\dot{s} + |s|^{2/3}\mathrm{sign}(s))}{|\ddot{s}| + 2(|\dot{s}| + |s|^{2/3})^{1/2}} \right] \quad (25)$$

Substitute this controller into (17) and letting $\psi_i = \delta_i + \gamma_i$, we have

$$\begin{aligned} \dot{V}_s = & -\sum_{i=1}^{3} s_i k_i [\ddot{s}_i + 2(|\dot{s}_i| + |s|_i^{2/3})^{-1/2}(\dot{s}_i + \\ & |s|_i^{2/3}\mathrm{sign}(s_i))]/[|\ddot{s}_i| + 2(|\dot{s}_i| + \\ & |s_i|^{2/3})^{1/2}] + \sum_{i=1}^{3} s_i \psi_i \quad (26) \end{aligned}$$

For the first term of (26) we take $\mathrm{sgn}(s_i)$ outside the bracket and

$$\begin{aligned} \dot{V}_s &= \sum_{i=1}^{3} s_i \psi_i - \sum_{i=1}^{3} k_i s_i \mathrm{sgn}(s_i)[\ddot{s}_i \mathrm{sgn}(s_i) + \\ & \quad 2(\dot{s}_i \mathrm{sgn}(s_i) + |s_i|^{2/3})^{-1/2}(\dot{s}_i \mathrm{sgn}(s_i) + \\ & \quad |s_i|^{2/3})]/[|\ddot{s}_i| + 2(|\dot{s}_i| + |s_i|^{2/3})^{1/2}] \\ &= \sum_{i=1}^{3} k_i |s_i| \{ \frac{\psi_i \mathrm{sgn}(s_i)}{k_i} - \\ & \quad \frac{\ddot{s}_i \mathrm{sgn}(s_i) + 2\frac{\dot{s}_i \mathrm{sgn}(s_i) + |s_i|^{2/3}}{(|\dot{s}_i| + |s_i|^{2/3})^{1/2}}}{|\ddot{s}_i| + 2(|\dot{s}_i| + |s_i|^{2/3})^{1/2}} \} \quad (27) \end{aligned}$$

To guarantee the reaching and sliding on the manifold, we require

$$\frac{\ddot{s}_i \mathrm{sgn}(s_i) + 2\frac{\dot{s}_i \mathrm{sgn}(s_i) + |s_i|^{2/3}}{(|\dot{s}_i| + |s_i|^{2/3})^{1/2}}}{|\ddot{s}_i| + 2(|\dot{s}_i| + |s_i|^{2/3})^{1/2}} \geq \frac{\psi_i \mathrm{sgn}(s_i)}{k_i}. \quad (28)$$

Since

$$\frac{\dot{s}_i \mathrm{sgn}(s_i) + |s_i|^{2/3}}{(|\dot{s}_i| + |s_i|^{2/3})^{1/2}} \leq (|\dot{s}_i| + |s_i|^{2/3})^{1/2}$$

and

$$\ddot{s}_i \mathrm{sgn}(s_i) \leq |\ddot{s}_i|$$

consequently we have

$$\frac{\ddot{s}_i \mathrm{sgn}(s_i) + 2(\dot{s}_i \mathrm{sgn}(s_i) + |s_i|^{2/3})^{-1/2}(\dot{s}_i \mathrm{sgn}(s_i) + |s_i|^{2/3})}{|\ddot{s}_i| + 2(|\dot{s}_i| + |s_i|^{2/3})^{1/2}} \leq 1 \quad (29)$$

Also the condition (28) can be written as

$$k_i \geq \psi_i \mathrm{sgn}(s_i). \quad (30)$$

The upper bound of $|\psi_i|$ can be found and denoted as

$$|\psi_i| < \psi_i^{max}(Q, \omega, q_d, \dot{q}_d, \ddot{q}_d). \quad (31)$$

Obviously, if we choose the gain k_i as $k_i \geq \psi_i^{max}(Q, \omega, q_d, \dot{q}_d, \ddot{q}_d)$ then $\dot{V}_s < 0$. This guarantees the reaching and sliding on the manifold.

VI. MULTIAXIAL ATTITUDE TRACKING MANOEUVRES

Here an example is presented with numerical simulation to validate and compare the various controllers; SMRSMC [4], QC2S and QC3S. The nominal part J_0 and the uncertain part ΔJ of the inertia matrix are

$$J_0 = \begin{bmatrix} 1200 & 0 & 0 \\ 0 & 2200 & 0 \\ 0 & 0 & 3100 \end{bmatrix}$$

and

$$\Delta J = \begin{bmatrix} 0 & 100 & -200 \\ 100 & 0 & 300 \\ -200 & 300 & 0 \end{bmatrix}$$

The initial conditions are $Q(0) = [0 \quad 0.5 \quad 0.5 \quad 0.7071]^T$, and $\omega(0) = [-0.0005 \quad 0.0008 \quad 0.001]^T$. Suppose that the external disturbance $d_i = 0$ and the workspace W is defined by $\beta^2 = 0.75$. The desired multiaxial attitude tracking manoeuvres are

$$q_d(t) = \begin{bmatrix} 0.5\cos[(\pi/50)t] \\ 0.5\sin[(\pi/50)t] \\ -0.5\sin[(\pi/50)t] \end{bmatrix}$$

and the magnitude constraints on the controllers are $|u_i| \leq 60(N \cdot m)$ for $i = 1, 2, 3$. For QC2S the positive scalar λ is selected as $\lambda = 1.2$ while for QC3S $\lambda = 0.19$. The sliding manifold is chosen as (11) with $K = \lambda I_3$ and the gains in the control laws are selected as $g_i = 60$ for $i = 1, 2, 3$.

Simulation results for the attitude tracking are shown in Figs. 1- 13. Figs. 1 and 3 show that the SMRSMC scheme gives good tracking output and the settling time is approximately 60 s. The sliding vector remains on the sliding manifold after 5 s. The actual control torques in Fig. 4 are very smooth. Regarding accuracy the bound on $|s|$ is 0.00047 (at steady state) with $O(h) = 0.005$ for $h = 0.005$.

As shown in Figs. 5 and 7, QC2S provides good tracking results. The settling time is approximately 35 s. In Fig. 6 the sliding vectors are driven to the sliding manifold and remain on the sliding manifold after 35 s. The actual control torques presented in Fig. 8 are limited by 60 N-m and but chattering appears in this system. Regarding accuracy the bound on $|s|$ is 0.00092 (at steady state) with $O(h) = 0.005$ for $h = 0.005$.

QC3S gives good tracking output(Figs. 9 and 11). The setting time is approximately 60 s. The sliding vector remains on the sliding manifold after 10 s. The calculated control torques shown in Fig. 13 are limited to 60 N-m. For the actual control torques applied to the spacecraft, Fig. 12 shows that the applied control torques are limited to 60 N-m for the first 15 s and then limited by 20 N-m, and are relatively smooth.Regarding accuracy the bound on $|s|$ is 0.000012 (at steady state) with $O(h^2) = 0.000025$ for $h = 0.005$.

Although QC2S gives a small settling time, it has severe chatter which is impractical for application to spacecraft attitude tracking. A smoothing scheme could reduce the chattering. Both SMRSMC scheme and and QC3S provides relatively smooth control torque signals. For accuracy QC3S obviously provides much more accurate tracking output. It gives outstanding accuracy (better than $O(h^2)$) while the accuracy of SMRSMC satisfies $O(h)$. In view of these simulation results, QC3S seem to be the most useful control design for practical spacecraft tracking, although its implementation is more complicated..

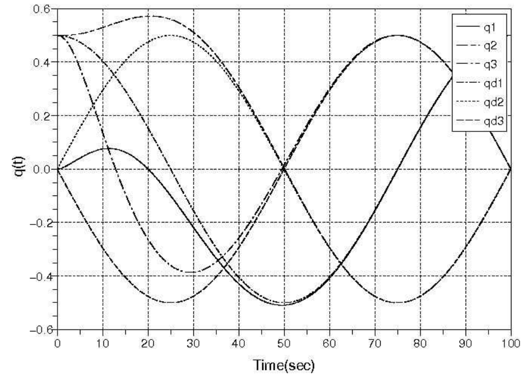

Fig. 1. Attitude tracking response (quaternions) - SMRSMC

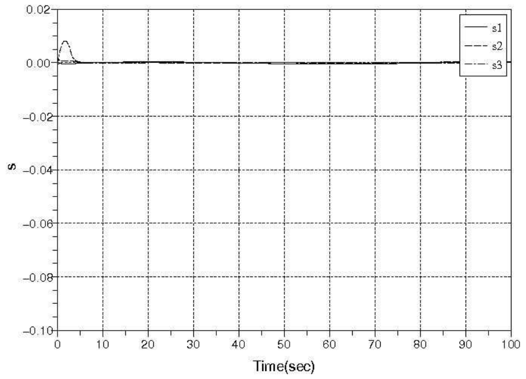

Fig. 2. Sliding functions - SMRSMC

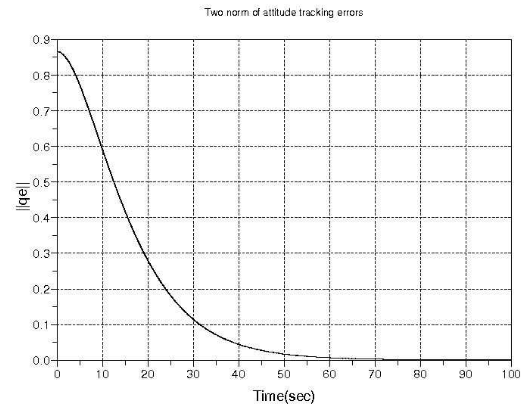

Fig. 3. Two norm of attitude tracking errors - SMRSMC

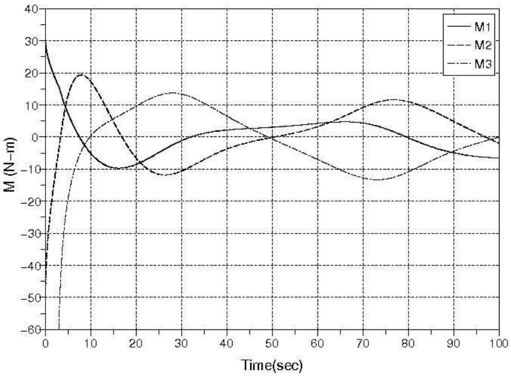

Fig. 4. Control torques - SMRSMC

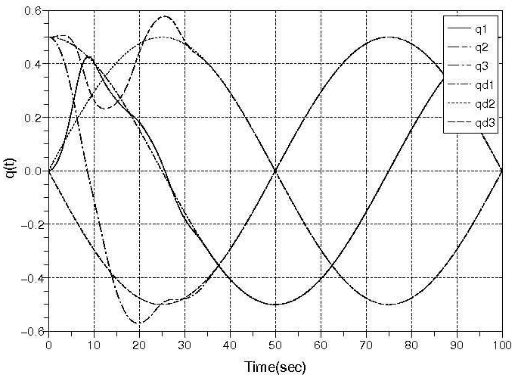

Fig. 5. Attitude tracking response(quaternions) - QC2S

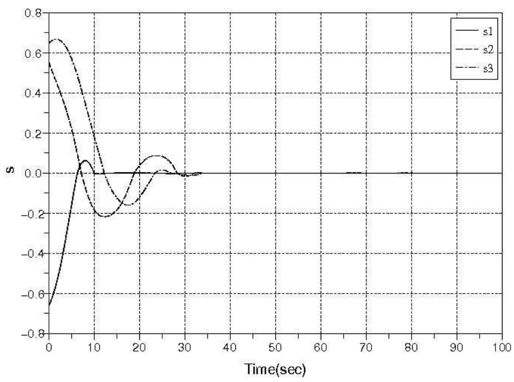

Fig. 6. Sliding functions - QC2S

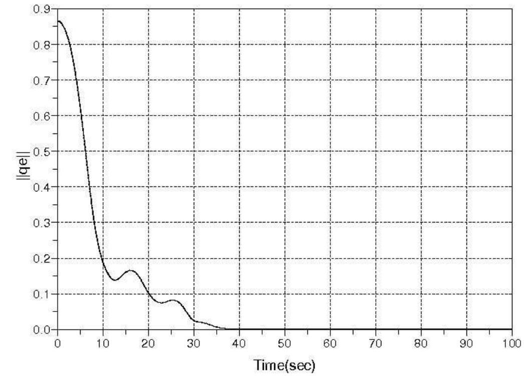

Fig. 7. Two norm of attitude tracking errors - QC2S

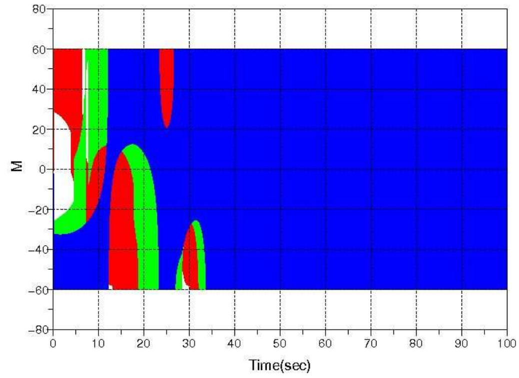

Fig. 8. Actual control torques - QC2S

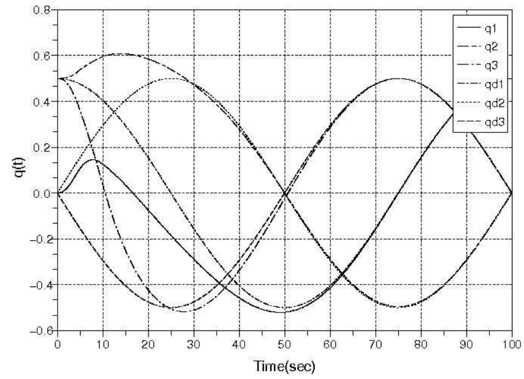

Fig. 9. Attitude tracking response (quaternions) - QC3S

VII. CONCLUSIONS

QC3S has been successfully applied to spacecraft attitude tracking manoeuvres. An example of spacecraft multiaxial attitude tracking manoeuvres has been presented. Moreover, it reduces the undesirable chattering effect induced in the conventional sliding mode control and QC2S, and provides very good accuracy of the tracking results. A class of linear sliding manifold is chosen as a function of angular velocities and quaternion errors. The second method of Lyapunov theory introduced to prove sliding system stability for all the controller designs.

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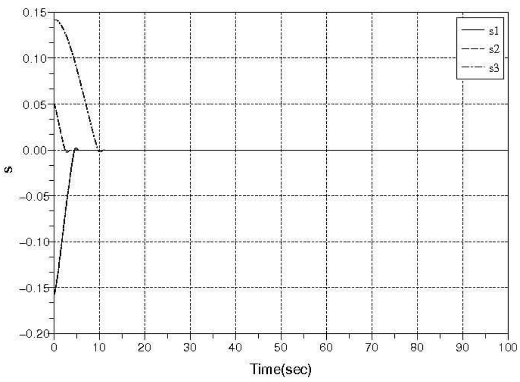

Fig. 10. Sliding functions - QC3S

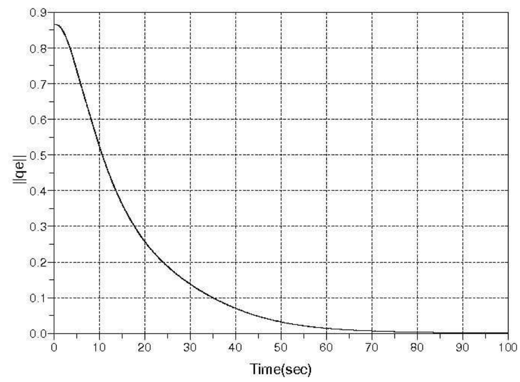

Fig. 11. Two norm of attitude tracking errors - QC3S

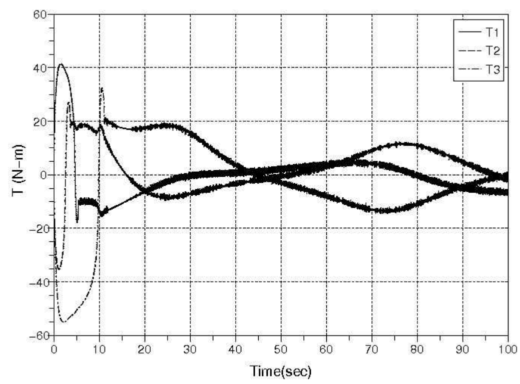

Fig. 12. Applied control torques - QC3S

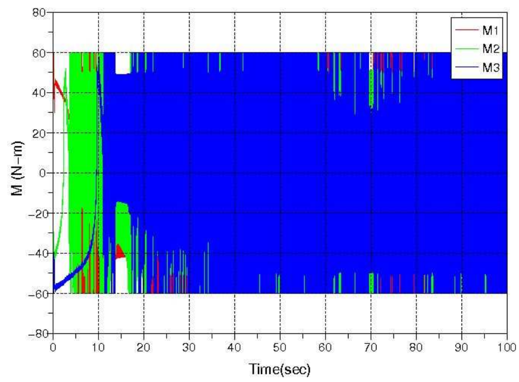

Fig. 13. Calculated control torques - QC3S.

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