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Feasibility Study of Switching Function Approaches in Sliding Mode Control for a Spacecraft's Attitude Control System

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***Abstract*—Sliding Mode Control (SMC) is well known as a robust control approach and is proven to be able to deal with nonlinear systems. To achieve this capability, the SMC controller input design is divided into two parts: a sliding surface design (continuous control) and a switching function design (discontinuous control). A spacecraft's attitude model is a multi-input and multi-output (MIMO) system and thus control design is difficult for some methodologies, however, in this case a SMC, is straightforward to construct. In this paper, for the continuous part, a reduction of order method (ROOM) is used to construct the sliding surface. For the discontinuous control, three different switching functions are designed and evaluated such as relays with constant gains, relays with state dependent gains and linear feedback with switched gains. The main contribution of this paper is to both analyse and investigate the limitations of these three switching functions at two different points (critical gains and proper gains) on a spacecraft's attitude model. The gains are selected using trial and error techniques as long as these gains meet the sufficiency conditions for the existence of a sliding mode. The discontinuous control is a high-speed switching function that produces chattering in the control input; however, solutions for chattering drawbacks are not discussed here. The best switching function is chosen based on the spacecraft's attitude transient performance requirements.**

Keywords: SMC, switching function, sliding surface, spacecraft's attitude

I. Introduction

In space, spacecraft positioning is challenged by disturbances and uncertainties such as sun UV, solar storms, atmospheric drag in low earth orbits and, sun and moon gravitational forces [1]. Hence, a robust controller is required to maintain the orientation of the spacecraft when these challenges occur. Criteria such as computational time, control power consumption and control output accuracy must be considered when designing an appropriate robust controller. These criteria are very important to make sure a spacecraft is successfully able to accomplish its missions in the prescribed period.

Among the possible robust control strategies, Sliding Mode Control (SMC) attributes such as low complexity, low computational burden, less weight and low cost control method make this a suitable approach to be implemented as a spacecraft attitude controller [2]. Adaptive Fuzzy SMC [3], Minimum Sliding Mode Error Feedback [4] and Integral SMC [5] have been successfully proposed for spacecraft attitude and orientation model. Furthermore, as spacecraft's attitude model is a multi-input and multi-output (MIMO) system, using SMC, the compensated system is easy to design. Thus, in this paper, SMC is chosen as the base methodology for designing a spacecraft attitude and orientation control law.

SMC control law design can be divided into two characteristic features (as expanded in Section III); the continuous and discontinuous control parts. The continuous part will drive the state trajectories of the controlled system onto the sliding surface in a prescribed manner while the discontinuous feature will maintain the states on the sliding surface [6]. There are various approaches to design the continuous part such as regular form and the reduced order dynamics, method of hierarchy and diagonalization methods [7] for a MIMO system. This paper, however, will use the reduction of order method (ROOM) to design the continuous part. The rationale for this is that in the ROOM method, the sliding surface coefficients can be chosen flexibly and thus looser assumptions can be made as long as the characteristic equation of the compensated system is comparable to the design criteria. For the discontinuous part (switching function), three approaches (relays with constant gain, relays with state dependent gains and linear continuous feedback) are evaluated on a known spacecraft attitude model [7].

It is important to understand the range of limitations of these SMC methods before further improvements can be made. Hence, the main novelty of this paper is to design and investigate the SMC control law with a focus on the switching function (SFD) characteristics and capability at two different points (critical gains and proper gains) for a spacecraft's attitude control. A notable part of the proposed approach is that some of the gains can be tuned using trial and error while satisfying some mild conditions to ensure the existence of a sliding mode. Characteristics such as chattering in the control inputs and transient response in the outputs are observed. Consequently, the switching function with most advantages is chosen as a basis for proposed improvements. On the other hand, ideally, the discontinuous control law must produce chattering due to a fast switching mechanism and discontinuous control across the sliding surface [8]. In this paper, approaches for chattering attenuation are not discussed and elimination techniques are proposed for future work.

The remainder of this paper is organized as follows. Section

II constructs the spacecrafts attitude model orbiting around earth. Section III designs and examines the SMC control law (ROOM and SFD) in a nonlinear uncertain MIMO system at two different situations. Next, Section IV analyses and evaluates the designed methods with special attention on potential improvements. Finally, conclusions and future proposals are presented in Section V.

II. Spacecraft's Attitude and Orientation Model

In this section, the rotational equation of motions (EOM) [9] of a spacecraft's rigid body in the body-fixed frame orbiting the earth with respect to an Earth Centered Inertial (ECI) (figure 1) are presented.

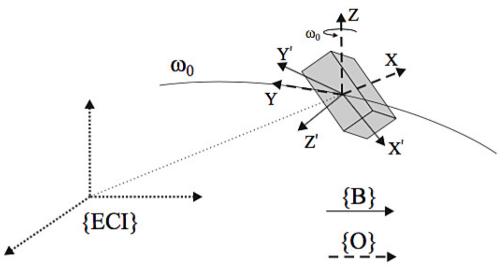

Figure 1. Spacecraft's attitude orbiting reference frame O, in moving frame B. Both are moving in ECI [10].

Consider the general form of a nonlinear system in state-space as in (1).

$$\dot{x}(t) = f(t,x) + B(u(t) + d(t)) \tag{1}$$

where $x(t)$ is a set of state variables, $f(t,x)$ is a nonlinear function, B is a $R^{m\times n}$ matrix, $u(t)$ is a set of inputs and $d(t)$ is the disturbances. Then, the EOM of a spacecraft are summarised as:

$$J\dot{\omega} = J\omega \times \omega + \tau \tag{2}$$

where J=diag(J_x,J_y,J_z) is the inertia tensor of rigid body, ω is spacecraft angular velocity, $\dot{\omega}$ is angular acceleration and τ is torque control input generated by the spacecraft's actuators. The vector ω has three rotational degrees of freedom (Z, Y, and X axes are denoted as yaw (ψ), pitch (θ) and roll (ϕ) respectively).

The absolute angular velocity ω_B of moving frame B is represented as follows where ω_{BO} is the velocity of B respect to O and ω_O is the velocity of O with respect to ECI.

$$\omega_B = \omega_{BO} + \omega_O; \quad \omega_B = \begin{bmatrix} \dot{\psi} - \omega_o\theta \\ \dot{\theta} + \omega_o\psi \\ \dot{\phi} + \omega_o \end{bmatrix} \tag{3}$$

Then, (3) is substituted into (2) with ω replaced by ω_B. Finally, the nonlinear spacecraft's attitude system is given by a form similar to (1) with:

$$\begin{aligned} \dot{x(t)} &= \begin{bmatrix} \dot{x_1} & \dot{x_2} & \dot{x_3} & \dot{x_4} & \dot{x_5} & \dot{x_6} \end{bmatrix}^T \\ f(t,x) &= \begin{bmatrix} x_2 & h & x_4 & i & x_6 & j \end{bmatrix}^T \\ B &= \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ u(t) &= \begin{bmatrix} \frac{\tau_x}{J_x} & \frac{\tau_y}{J_y} & \frac{\tau_z}{J_z} \end{bmatrix} \end{aligned} \tag{4}$$

where $\begin{bmatrix} \psi & \dot{\psi} & \theta & \dot{\theta} & \phi & \dot{\phi} \end{bmatrix}$ are replaced by $\begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 \end{bmatrix}$ respectively and

$$\begin{aligned} h &= (\tfrac{J_y - J_z + J_x}{J_x})\omega_o x_4 - (\tfrac{J_y - J_z}{J_x})(x_4 x_6 + x_1 x_2 \omega_o + x_1 \omega_o^2); \\ i &= (\tfrac{J_z - J_x - J_y}{J_y})\omega_o x_2 + (\tfrac{J_z - J_x}{J_y})(x_2 x_6 - x_3 x_5 \omega_o - x_3 \omega_o^2); \\ j &= (\tfrac{J_x - J_y}{J_z})(x_2 x_4 - x_3 x_4 \omega_o + x_1 x_2 \omega_o - x_1 x_3 \omega_o^2); \end{aligned}$$

In conclusion, the spacecraft's attitude model is a MIMO system where the inputs $u(t)$ are the torques τ_x, τ_y, τ_z generated by actuators while the outputs are the spacecraft's angular velocity in the X, Y and Z directions.

III. Control Law Design in SMC

In this section, the constructions of SMC control law are presented. There are two stages to design the control law (U_i) that is continuous (U_{eq}) and discontinuous (U_N) control.

$$U_i = U_N + U_{eq} \tag{5}$$

In this paper, the first part (continuous control (U_{eq})) is designed by manipulating the inputs of the uncompensated system using ROOM by introducing sliding surfaces. ROOM is chosen because this method is suitable and easy to design for a MIMO system.

The main contribution of this paper is focussed on the second part of the control design. In the discontinuous control (U_N) component, three alternative approaches are designed and deployed; relays with constant gains (RCG), relays with state dependent gains (RSG) and linear feedback with switched gains (LFSG) [7]. Hence, the specific novelty in this section is the construction of the switching function at two different points (critical gains and proper gains **[NOT DEFINED THESE TERMS YET!]**) in order to observe their constraints. Thereafter, the performances of the alternative switching functions are evaluated and compared. **UNCLEAR On the other hand, the gains (which ones) are tuning using trial and error technique as long as the values are fulfill the conditions for the existence of a sliding mode (needs to be clarified).**

A. Sliding Surface Design using Reduction of Order Method

The basic method in SMC is to design a set of switching surfaces ($\sigma(x)$). The behavior of a switching surface is illustrated in figure 2 [1]. The $\sigma(x)$ line is designed to cross the origin (target) to make sure the compensated system is robust to disturbances and uncertainties. The switching surface equation and the dynamics equation where S is the sliding surface are summarised as:

$$\sigma(x) = Sx = 0 \tag{6}$$

$$\dot{\sigma}(x) = S\dot{x} = 0 \tag{7}$$

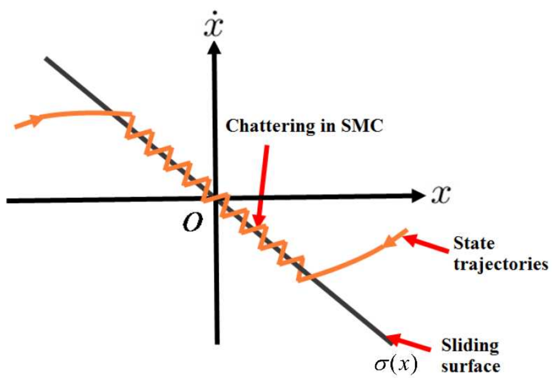

Figure 2. Phase-plane of the closed loop system for second order system.

The spacecraft's attitude model is a multi-input (3 inputs) and multi-output (3 outputs) system. Hence, three sliding surfaces (S_1, S_2, and S_3) are required for the spacecraft's attitude model:

$$S = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & s_{14} & s_{15} & s_{16} \\ s_{21} & s_{22} & s_{23} & s_{24} & s_{25} & s_{26} \\ s_{31} & s_{32} & s_{33} & s_{34} & s_{35} & s_{36} \end{bmatrix} \tag{8}$$

In this paper, and with the spacecraft's attitude model to be used, it is appropriate to have the characteristic equation at $\lambda^3+6\lambda^2+11\lambda+6$ with poles at -1, -2 and -3; the selection of the characteristic equation is made in order to allow the spacecraft's attitude converge to the zero less than 100 seconds [11]. Thus, some assumptions on the sliding surface coefficients (s_{ij}) are needed to ensure this characteristic equation is achieved.

B. ROOM design

The sliding surface design using ROOM is as follows. Firstly, (1) is replaced in (7) and produces:

$$S\dot{x} = S(f(t,x) + B(U_{eq} + d(t))) = 0 \tag{9}$$

Now, $u(t)$ become control law U_{eq} (the continuous part). Hence:

$$U_{eq} = -(SB)^{-1}(Sf(t,x) + SBd(t)) \tag{10}$$

Then, (10) is substituted into (1) and produces :

$$\dot{x} = [I - B(SB)^{-1}S]f(t,x) \tag{11}$$

In ROOM, assumptions can be made on the s_{ij} values and can be chosen flexibly. First define SB

$$SB = \begin{bmatrix} s_{12} & s_{14} & s_{16} \\ s_{22} & s_{24} & s_{26} \\ s_{32} & s_{34} & s_{36} \end{bmatrix} \tag{12}$$

The determinant of SB can be set to any value as long as $|SB| \neq 0$ and $s_{ij} \geq 0$. To simplify the design process, assume $|SB| = 1$. One of the combinations to set $|SB| = 1$ is to let $s_{12} = s_{14} = s_{22} = s_{26} = s_{32} = s_{34} = s_{36} = 1$, $s_{24} = 2$ and $s_{16} = 0$.

Thus, based on these selections, then:

$$(SB)^{-1} = \begin{bmatrix} 1 & -1 & 1 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \tag{13}$$

Next, substitute (4), (8) and (13) into (11) so the dynamic model is reduced to:

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \\ \dot{x_5} \\ \dot{x_6} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & a & 0 & b & 0 & c \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & d & 0 & e & 0 & f \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & h & 0 & i \end{bmatrix} \tag{14}$$

where

$$\begin{aligned} a &= s_{21} - s_{11} - s_{31}; & b &= s_{23} - s_{13} - s_{33}; \\ c &= s_{25} - s_{15} - s_{35}; & d &= s_{31} - s_{21}; \\ e &= s_{33} - s_{23}; & f &= s_{35} - s_{25}; \\ g &= s_{11} - s_{31}; & h &= s_{13} - s_{33}; \\ i &= s_{15} - s_{35}; \end{aligned}$$

Finally, using (7) and (14), the reduced order model of the spacecraft's attitude system is:

$$\dot{\hat{x}} = \begin{bmatrix} \dot{\hat{x_1}} \\ \dot{\hat{x_2}} \\ \dot{\hat{x_3}} \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \tag{15}$$

where $\dot{\hat{x_1}} = \dot{x_2}$, $\dot{\hat{x_2}} = \dot{x_4}$ and $\dot{\hat{x_3}} = \dot{x_6}$.

In this design, the characteristic equation of (15) is matched to $\lambda^3+6\lambda^2+11\lambda+6$, in order to achieve zero steady state error less than 100 seconds [11]. Hence, the expanded characteristic equation of (15) is given as:

$$\begin{aligned} \Delta(\dot{\hat{x}}) \;=\; & \lambda^3 + (s_{11} - s_{15} - s_{21} + s_{23} + s_{31} - s_{33} + s_{35})\lambda^2 \\ & +(s_{11}s_{23} - s_{13}s_{21} - s_{11}s_{25} + s_{15}s_{21} + s_{13}s_{25} \\ & -s_{15}s_{23} - s_{11}s_{33} + s_{13}s_{31} + 2s_{11}s_{35} - 2s_{15}s_{31} \\ & -s_{13}s_{35} + s_{15}s_{33} - s_{21}s_{35} + s_{25}s_{31} + s_{23}s_{35} \\ & -s_{25}s_{33})\lambda + (s_{11}s_{23}s_{35} - s_{11}s_{25}s_{33} - s_{13}s_{21}s_{35} \\ & +s_{13}s_{25}s_{31} + s_{15}s_{21}s_{33} - s_{15}s_{23}s_{31}) \end{aligned} \tag{16}$$

and the implied constraints on the values s_{ij} are given as:

$$\begin{aligned}
&s_{11}-s_{15}-s_{21}+s_{23}+s_{31}-s_{33}+s_{35} &=& \;6\\
&s_{11}s_{23}-s_{13}s_{21}-s_{11}s_{25}+s_{15}s_{21}+s_{13}s_{25}\\
&-s_{15}s_{23}-s_{11}s_{33}+s_{13}s_{31}+2s_{11}s_{35}-2s_{15}s_{31}\\
&-s_{13}s_{35}+s_{15}s_{33}-s_{21}s_{35}+s_{25}s_{31}\\
&+s_{23}s_{35}-s_{25}s_{33} &=& \;11\\
&s_{11}s_{23}s_{35}-s_{11}s_{25}s_{33}-s_{13}s_{21}s_{35}\\
&+s_{13}s_{25}s_{31}+s_{15}s_{21}s_{33}-s_{15}s_{23}s_{31} &=& \;6
\end{aligned} \quad (17)$$

In this paper we will define $s_{13} = 0.5$, $s_{15} = 4$, $s_{23} = 3$, $s_{25} = 2$, $s_{31} = 1$ and $s_{35} = 2$ and then use these values in combination with (17) to solve for the remaining coefficients s_{ij}. Thus:

$$\begin{aligned}
s_{11}-s_{21}-s_{33}+2 &= 6\\
5s_{11}+1.5s_{21}+2s_{33}-s_{11}s_{33}-11.5 &= 11\\
6s_{11}-s_{21}-2s_{11}s_{33}+4s_{21}s_{33}-11 &= 6
\end{aligned} \quad (18)$$

Solving (18), then $s_{11} = 5.5303$, $s_{21} = 0.0623$ and $s_{33} = 1.468$. Finally, the sliding surface design of (8) is given as follows:

$$S = \begin{bmatrix} 5.5303 & 1 & 0.5 & 1 & 4 & 0\\ 0.0623 & 1 & 3 & 2 & 2 & 1\\ 1 & 1 & 1.468 & 1 & 2 & 1 \end{bmatrix} \quad (19)$$

In conclusions, using the ROOM approach there are 18 coefficients which have to be selected to define the sliding surface design. This gives a huge amount of flexibility to the designer. In principle one can meet the required dynamics for the sliding mode by choosing 15 coefficients and then solving for the remaining 3 to ensure sure the compensated system meets the design criteria. This paper does not explore how this flexibility might be exploited in general. **HOWEVER, READERS MIGHT WANT SOME REFERENCES TO FOLLOW UP OR HINTS AS THIS SEEMS TOO ARBITRARY**

C. Switching Function Design (SFD)

There are three popular variants of SFD (RCG, RSG and LFSG) which are discussed in this section and for two different scenarios which are critical gains and proper gains. The general form of RCG, RSG and LFSG are shown in Table I.

1) Relays with constant gains (RCG): The rules to meet the sufficiency condition for the designed SMC is $\sigma\dot{\sigma} = \alpha_i\sigma_i(x)sgn(\sigma_i(x)) < 0$, if $\sigma_i(x) \neq 0$. α_i is a constant tuning gain **(NEED INSIGHT INTO CHOICE)** where the value must be negative $\alpha_i < 0$. The stability condition for RCG is:

Table I
EXISTING SWITCHING FUNCTION CONTROL ALGORITHM

SFD	Algorithm	Condition
RCG	$U_{iN}(x) = \begin{cases}\alpha_i sgn(\sigma_i(x)), \\ 0\end{cases}$	$\sigma_i(x) \neq 0$ $\sigma_i(x) = 0$
RSG	$U_{iN}(x) = \begin{cases}\alpha_i(x) sgn(\sigma_i(x)), \\ 0\end{cases}$	$\sigma_i(x) \neq 0$ $\sigma_i(x) = 0$
LFSG	$U_N(x) = -L\sigma(x)$	L is symmetric positive definite constant matrix

$$\begin{aligned}
\sigma_i(x)\dot{\sigma_i}(x) &= \alpha_i\sigma_i(x)sgn(\sigma_i(x)) < 0\\
&= \alpha_i\tfrac{\sigma_i^2(x)}{|\sigma_i(x)|}
\end{aligned}$$
Let,
$$\alpha_i = -0.001 \quad (20)$$
Then,
$$\begin{aligned}
\sigma_i(x)\dot{\sigma_i}(x) &= -0.001\tfrac{\sigma_i^2(x)}{|\sigma_i(x)|}\\
&< 0
\end{aligned}$$

2) Relays with state dependent gains (RSG): The stability rules for the RSG controller are $\sigma\dot{\sigma} = \alpha_i(x)\sigma_i(x)sgn(\sigma_i(x)) < 0$, if $\sigma_i(x) \neq 0$. $\alpha_i(x)$ is a variable states function where $\alpha_i(x) = \beta_i(\sigma_i^{2k}(x) + \gamma_i)$ with $\beta_i < 0$, $\gamma_i > 0$ and k is an integer number.

$$\begin{aligned}
\sigma_i(x)\dot{\sigma_i}(x) &= \alpha_i(x)\sigma_i(x)sgn(\sigma_i(x)) < 0\\
\alpha_i(x) &= \beta_i(\sigma_i^{2k}(x) + \gamma_i)
\end{aligned}$$
Let,
$$\beta_i(x) = -1, \gamma_i = 0.001, k = 1$$
Then,
$$\begin{aligned}
\sigma_i(x)\dot{\sigma_i}(x) &= -1(\sigma_i(x)^2 + 0.001)\tfrac{\sigma_i(x)^2}{|\sigma_i(x)|}\\
&< 0
\end{aligned} \quad (21)$$

where here the design choices are *********give rationale*******

3) Linear feedback with switched gains (LFSG): The stability condition for LTSG is $\sigma^T(x)\dot{\sigma}(x)$=$-\sigma^T(x)L\sigma(x) < 0$, if $\sigma(x) \neq 0$, L is a symmetric positive definite constant matrix, $L \in R^{mxm}$. In this paper, L is a 3x3 matrix

$$L = \begin{bmatrix} w & y & z\\ y & w & y\\ z & y & w \end{bmatrix} \quad (22)$$

w, y and z values are given in table II. **again some rationale is needed**

4) Critical Gains and Proper Gains: There are two different gains (critical gains and proper gains) where analysis of performance are made on these switching functions designs listed in Table I. The aims is to explore the limitations of the SFD performances an gain insight into how alternative proposals may be better suited to the given application. A particular noteworthy point is that the gains in Table II are

Table II
GAIN SELECTION FOR SFD

SFD	RCG	RSG		LFSG
	α_i	β	γ	L
Critical Gain	-0.01	-1	0.01	w=0.02, y=0.01, z=0
Proper Tuning	-0.000001	-1.0	0.000001	w=0.000002, y=0.000001, z=0

typically selected using trial and error techniques to meet the conditions in table I and there is clearly a need for a more systematic approach and insight into the repercussions of the decisions taken.

IV. RESULTS

To perform and evaluate the designed control law with a real case situation, next this paper considers the spacecraft's attitude model in (4) with numeric parameters as in Table III. The selection of inertia tensor, J_x, J_y and J_z is based on the International Space Station (ISS) [9] values. This section will present the simulation results of the nonlinear system with and without the SMC switching function approaches. The results are divided into two parts; angular rate response at critical gains, and proper gains and control input. For the first subsection the transient response of the angular rate for both gains selections are observed while the chattering phenomena is analyzed in the second subsection.

Table III
NUMERIC PARAMETERS OF SPACECRAFT'S ATTITUDE SYSTEM

Parameter	Value	Unit
ω_o	0.0011	$rads^{-1}$
J_x	127538483.85	kgm^2
J_y	201272329.17	kgm^2
J_z	106892554.98	kgm^2
τ_x, τ_y, τ_z	1×10^{-3}	N
$d(t)$	$sin(t)$	N

A. Angular Velocity of Spacecraft's Attitude System

Figures 3 and 4 show the angular rate response of the uncompensated (open-loop) spacecraft's attitude system and the same system in closed-loop with RCG, RSG and LFSG, for critical gains and proper gains respectively.

- For critical gains, the uncompensated system shows that the outputs for yaw, pitch and roll do not settle at zero steady state error and thus closed-loop control is needed.
- For RCG, the outputs settle around 120 seconds with chattering at an amplitude at 0.02 $rads^{-1}$.
- RSG shows a chattering amplitude similar to RCG (0.02 $rads^{-1}$) but converges faster in around 40 seconds.
- With LFSG, the angular velocity shows no chattering in the outputs, but the convergence is somewhat slower at 280 seconds.

For the proper gains selections in figure 4, all the SFD methods show zero steady state error with no discernible chattering. With RCG and LFSG the angular rates converge to the equilibirium point in around 10 seconds whereas RSG takes around 100 seconds to achieve the equilibirium point. Again the open-loop response does not converge. The summary of SFD performances is summarised in Tables IV and V.

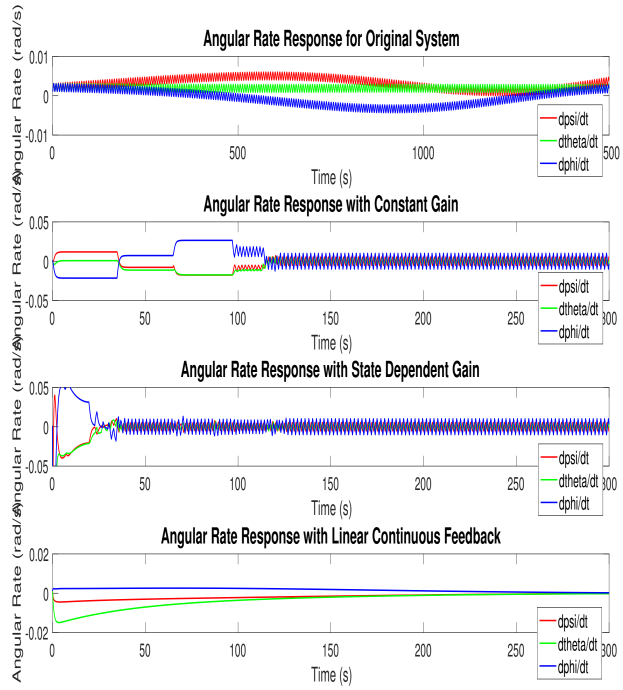

Figure 3. Angular Rate Response of the Uncompensated and Compensated System at the Critical Gain

Table IV
ANGULAR RATE RESPONSE AT THE CRITICAL GAIN

	Original System	RCG	RSG	LFSG
Steady State Error	Yes	Yes	Yes	No
Chattering	Yes	Yes	Yes	No
Chattering Amplitude		$0.02 rads^{-1}$	$0.02 rads^{-1}$	0
Settling Time		120 s	40 s	280 s

Table V
ANGULAR RATE RESPONSE AT THE PROPER GAIN

	Original System	RCG	RSG	LFSG
Steady State Error	Yes	No	No	No
Settle Time		10 s	100 s	10 s

B. Control Inputs of Spacecraft's Attitude System

Looking at the control inputs in figure 5, all the SFD methods show some chattering with an amplitude of 0.1 $rads^-1$. RSG, however, takes 5 seconds to converge to the chattering amplitude compared to RCG and LFSG methods where the chattering begins immediately.

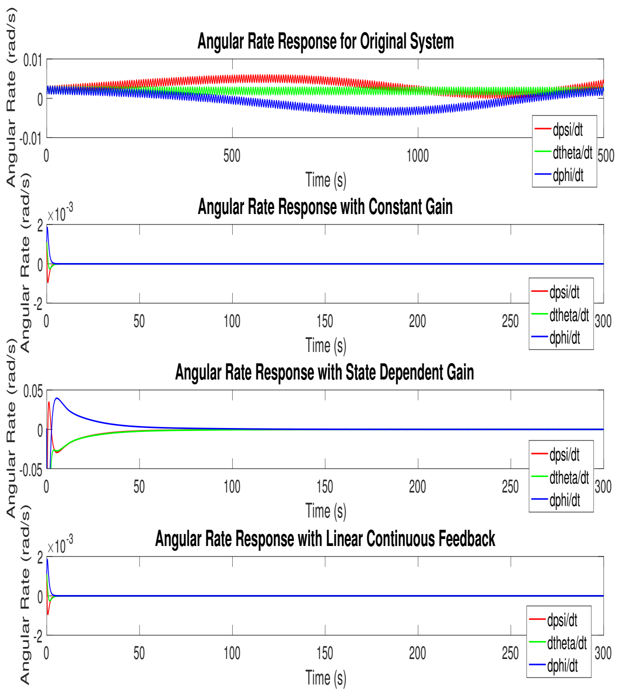

Figure 4. Angular Rate Response of the Uncompensated and Compensated System at the Proper Gain

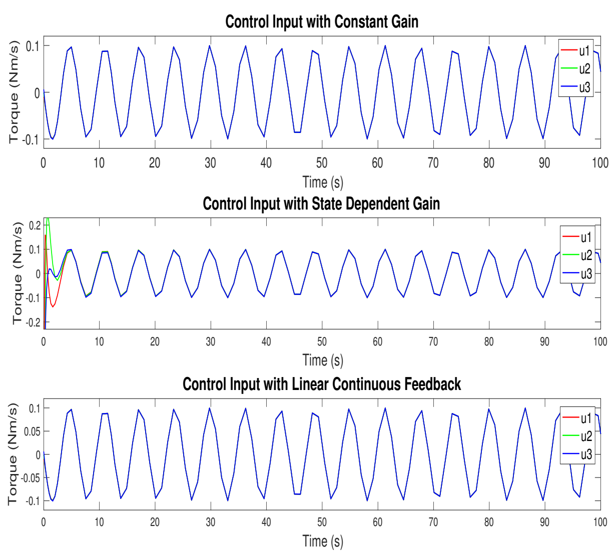

Figure 5. Control Input of the Compensated System

V. Conclusions and Future Recommendations

This paper has focused on the potential uses of SMC methods for spacecraft attitude control and specifically designs and contrasts three common algorithms.

SMC approaches can produce high control accuracy but the occurrence of a chattering phenomena is a significant drawback. The results sections shows that at the critical gains, LSFG gives an angular velocity which is free from chattering compared to RCG and RSG. For the proper gains, all techniques give outputs which are free from chattering. However, the gain selection for proper analysis is small and in general the gains may be quite difficult to tune to the require for some trial and error and moreover higher gains may be over sensitive to measurement noise. **THIS LAST SENTENCE IS UNCLEAR**

In conclusion, the LFSG method shows a better performance as there is no chattering in the angular velocity outputs at the critical gains compared to RCG and RSG (both are producing chattering in the outputs) for spacecraft's attitude model (see table IV). Thus, LFSG will be the preferred option to design the SMC control law for this system for future studies. However. it is noted that a modification in LFSG is required in order to attenuate the chattering in the control input. Some possible modifications to explore include higher order sliding mode control [12], variable gain super-twisting sliding mode control [13] and decaying boundary layer and switching function method thorough error feedback [2].

A bit more information on next steps and desired benefits would help. How improve compared to existing ideas? Also any comments on tuning steps which were trial and error? Why is your comparison a useful contribution to the field? What is significance of this contribution? Analysis/evaluation rather limited, could you say more? Also, vague on performance requirements.

VI. Acknowledgements

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