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Fuzzy Sliding Mode Attitude Control of Satellite

X.J. Liu, P. Guan, and J.Z. Liu

Abstract—The adaptive fuzzy sliding mode control is applied to the attitude stabilization of flexible satellite. The detailed design procedure of the fuzzy sliding mode control system is presented. The adaptive fuzzy control is utilized to approach the equivalent control of sliding mode control and the adaptive law is derived. The hitting control, which guarantees the stability of the control system, is developed. In order to attenuate the chattering phenomena, fuzzy rules are employed to smooth the hitting control. Simulation results show precise attitude control is accomplished based on the proposed method.

I. Introduction

FUTURE spacecraft will be expect to achieve highly accurate pointing and fast slewing in the presence of large environmental disturbances, large uncertainties and flexible appendages. However, flexible satellite is the complex system with high nonlinearity, uncertainty and disturbance. Therefore satellite attitude control design needs take into account parametric uncertainty and disturbance rejection. Sliding mode control (SMC) has emerged to be a robust control technique for satellite attitude control, due to its insensitiveness to system uncertainty and external disturbance when sliding motion occurs. A known major drawback of SMC is chattering. To avoid chattering phenomena, the sign function in the control law is replaced by the saturation function [1][2], or by an approximate sign function [3]. The cost of such substitution is a reduction in the accuracy of the desired performance. Recently, some investigators integrate fuzzy set theory into SMC to construct the fuzzy sliding mode control (FSMC) for attenuating the chattering phenomena. In [4][5], fuzzy control and SMC are incorporated to achieve a robust control process. The high computing burden of these complicated algorithms may limit their on-line application to satellites. Paper [6] use fuzzy control rules to construct the nonlinear control of SMC. The chattering phenomena are effectively attenuated. However, the nonlinear control based on the fixed fuzzy rule possesses weak adaptability to the uncertainties of satellite. This can affect the performance of the fuzzy sliding mode controller.

Constituting more computing efficient adaptive mechanism on SMC is essential for satellite attitude control.

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In contrast to the above work, this article presents an application of the adaptive fuzzy sliding mode control (AFSMC) in the attitude stabilization of the flexible satellite. The three adaptive fuzzy sliding mode controllers are developed to respectively control the three-axis attitude. The employed sliding mode control law is separated into two parts: the equivalent control term and the hitting control term. The adaptive fuzzy control is used to approximate the equivalent control via rules regulation in order to obtain the suitable equivalent control in the presence of the satellite parameters uncertainties and the external disturbance. Then, the hitting control is appended to guarantee the stability of the proposed AFSMC. Moreover, a set of heuristic control rules is constructed to attenuate the chattering phenomenon of the hitting control signal. As a result, this control algorithm is computationally simple, assure fast and accurate attitude response in the satellite control system.

The rest of this paper is organized as follows. Section 2 describes the satellite attitude control problem. Section 3 constructs an AFSMC controller based on the principle of sliding mode, and develops a direct adaptive mechanism to adjust the control rules for obtaining the equivalent control. The designing of the hitting control that guarantees the stability of the system is also derived. In section 4, simulation results are provided to illustrate the performance of the proposed method. Finally, a brief conclusion is given in section 5..

II. Problem Formulation

The flexible satellite with a solar panel moving in a circular orbit, driven by the reaction wheels in the steady operation is considered. By using Newton-Euler equation, the equations of motion for the three-axes stabilizing flexible satellite are derived as follows:

$$J\dot{\omega} + \omega^{\times}(J\omega + J_s\Omega_s) + C_0\ddot{\eta} = T_d + u\,, \quad u = -J_s\dot{\Omega}_s \tag{1}$$

$$\ddot{\eta} + 2\xi\Lambda\dot{\eta} + \Lambda^2\eta + C_0{}^T\dot{\omega} = 0 \tag{2}$$

$$\omega_1 = \dot{\theta}_1 - \omega_0\theta_3\,,\ \omega_2 = \dot{\theta}_2 - \omega_0\,,\ \omega_3 = \dot{\theta}_3 + \omega_0\theta_1 \tag{3}$$

Where $J = diag(J_1, J_2, J_3)$ denotes inertia matrix; $\theta = [\theta_1\ \theta_2\ \theta_3]^T$ denotes satellite attitude angle vector (θ_1, θ_2, θ_3 are respectively the roll, pitch, yaw angles); $\omega = [\omega_1\ \omega_2\ \omega_3]^T$ denotes the angular velocity of the satellite with respect to an inertial frame; $J_s\Omega_s = [J_{s1}\Omega_{s1}\ \ J_{s2}\Omega_{s2}\ \ J_{s3}\Omega_{s3}]^T$ denotes the angular momentum of the reaction wheels; ω_0 denotes the orbital

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angular velocity; $u \in R^3$ denotes the vector of control torques; $T_d \in R^3$ denotes the vector of external disturbances; C_0 is the coupling matrix between rigid body and appendage; η is the vector of second-order modal displacements, ξ is the modal damping matrix; Λ is modal frequency matrix.

For any vector $r = [r_1 \ r_2 \ r_3]^T$, the notation $r^{\times}$ stands for cross product matrix:

$$r^{\times} = \begin{bmatrix} 0 & -r_3 & r_2 \\ r_3 & 0 & -r_1 \\ -r_2 & r_1 & 0 \end{bmatrix}.$$

Define state variable $z = [\theta_1 \ \dot{\theta}_1 \ \theta_2 \ \dot{\theta}_2 \ \theta_3 \ \dot{\theta}_3]^T = [z_1 \ z_2 \ z_3 \ z_4 \ z_5 \ z_6]^T$, the equations of motion for the satellite can be put in the form of following three uncertain nonlinear subsystems:

Roll subsystem:

$$\begin{cases} \dot{z}_1 = z_2 \\ \dot{z}_2 = f_1(z) + g_1(z)u_1 + d_1 \end{cases} \tag{4}$$

where

$$f_1(z) = \frac{J_2 - J_3}{J_1}(z_4 z_6 + \omega_0 z_1 z_4 - \omega_0 z_6 - \omega_0^2 z_1) + \omega_0 z_6$$

$$g_1(z) = \frac{1}{J_1},$$

$$d_1 = \frac{-c_{11}\ddot{\eta}_1 - c_{12}\ddot{\eta}_2 + T_{d1}}{J_1} + \frac{J_{s2}\Omega_{s2}}{J_1}(z_6 + \omega_0 z_1) - \frac{J_{s3}\Omega_{s3}}{J_1}(z_4 - \omega_0),$$

d_1 and u_1 respectively denote the disturbance and control torques in roll subsystem.

Pitch subsystem:

$$\begin{cases} \dot{z}_3 = z_4 \\ \dot{z}_4 = f_2(z) + g_2(z)u_2 + d_2 \end{cases} \tag{5}$$

where $f_2(z) = \dfrac{J_3 - J_1}{J_2}(z_2 z_6 + \omega_0 z_1 z_2 - \omega_0 z_5 z_6 - \omega_0^2 z_1 z_5)$

$$g_2(z) = \frac{1}{J_2},$$

$$d_2 = \frac{-c_{21}\ddot{\eta}_1 - c_{22}\ddot{\eta}_2 + T_{d2}}{J_2} - \frac{J_{s1}\Omega_{s1}}{J_2}(z_6 + \omega_0 z_1) + \frac{J_{s3}\Omega_{s3}}{J_2}(z_2 - \omega_0 z_5),$$

d_2 and u_2 respectively denote the disturbance and control torques in pitch subsystem.

Yaw subsystem:

$$\begin{cases} \dot{z}_5 = z_6 \\ \dot{z}_6 = f_3(z) + g_3(z)u_3 + d_3 \end{cases} \tag{6}$$

where

$$f_3(z) = \frac{J_1 - J_2}{J_3}(z_2 z_4 + \omega_0^2 z_5 - \omega_0 z_2 - \omega_0 z_4 z_5) - \omega_0 z_2$$

$$g_3(z) = \frac{1}{J_3},$$

$$d_3 = \frac{-c_{31}\ddot{\eta}_1 - c_{32}\ddot{\eta}_2 + T_{d3}}{J_3} + \frac{J_{s1}\Omega_{s1}}{J_3}(z_4 - \omega_0) - \frac{J_{s2}\Omega_{s2}}{J_3}(z_2 - \omega_0 z_5),$$

d_3 and u_3 respectively denote the disturbance and control torques in yaw subsystem.

Based on the above derivation, the dynamic equations of the satellite can be decomposed into three subsystems. ($f_i(z)$, $g_i(z)$) denotes one subsystem, i=1,2,3. The three adaptive fuzzy sliding mode controllers are similarly employed to control respectively roll, pitch, yaw subsystem. Each subsystem may be written as the form of the single input nonlinear system.

$$\begin{cases} x^{(n)} = f(x) + g(x)u + d \\ y = x \end{cases}, \ n=2 \tag{7}$$

Where $u \in R$ and $y \in R$ are control torque and system output. *f(x)* is a nonlinear continuous function whose upper bound is known as $|f(x)| \le f_{\max}$. *g(x)* is a gain function with lower bound $g_{\min}$, $0 < g_{\min} \le g(x)$. d is the bound disturbance, $|d| \le d_{\max}$.

Satellite commonly operates in the presence of various disturbances. The inertia matrix *J* of satellite is usually not known exactly. In addition, oscillation of the flexible appendage also influence satellite attitude. All these can lead to the satellite attitude uncertainty. Therefore, the function *f* and g are uncertain in satellite attitude control system. The control task is to find a suitable control law *u* to force the system output *y* to follow a given reference signal *r* in spite of the bound disturbance and the uncertainty in the system, i.e. $\vec{\theta}_i(t) \to 0$, $\dot{\vec{\theta}}_i(t) \to 0$ as $t \to \infty$, *i=1,2,3.*

III. Adaptive Fuzzy Sliding Mode Controller

Define the error *e=r-y*, and the state variable $\dot{x}_i = x_{i-1}$ *(i=1,2,…,n).* The state vector x is given as $\mathrm{x} = [x_1, x_2, ..., x_n]^T = [x, \dot{x}, ..., x^{(n-1)}]^T \in R^n$, the error state vector e is defined as $\mathrm{e} = [e_1, e_2, ..., e_n]^T = [e, \dot{e}, ..., e^{(n-1)}]^T \in R^n$. The nonlinear system (7) can be rewritten as the error vector form:

$$\begin{bmatrix} \dot{e}_1 \\ \vdots \\ \dot{e}_{n-1} \\ \dot{e}_n \end{bmatrix} = \begin{bmatrix} e_2 \\ \vdots \\ e_n \\ -f - gu - d + r^{(n)} \end{bmatrix} \tag{8}$$

Suppose the sliding surface be given as:

$$S=\lambda^T \mathrm{e} \tag{9}$$

Where $\lambda=[\lambda_1,\lambda_2,...,\lambda_{n-1},1]^T$ is the coefficient vector of sliding surface specified by the designer. In the design of sliding mode controller, an equivalent control is first given so that the states can stay on sliding surface. Thus in sliding motion, the system dynamic is independent of the original system and a stable equivalent control system is achieved. The equivalent control can be obtained by letting $\dot{S}$ equal to zero. That is:

$$\dot{S}=\lambda^T\dot{\mathrm{e}}=\lambda_m^T\mathrm{e}+(-f-gu-d+r^{(n)})=0 ,$$

$$\lambda_m=[0,\lambda_1,\lambda_2,...,\lambda_{n-1}]^T \tag{10}$$

$$u_{eq}=g^{-1}(\lambda_m^T\mathrm{e}-f-d+r^{(n)}) \tag{11}$$

While state trajectory slides on the surface S=0, an equivalent (n-1)th-order stable system yields:

$$e^{(n-1)}+\lambda_{n-1}e^{(n-2)}+\cdots+\lambda_2\dot{e}+\lambda_1 e=0 \tag{12}$$

The coefficient λ can be properly chosen such that all the roots in (12) are in the open left-half of the complex plane. That is, if the state trajectory can be forced to slide on sliding surface, a stable equivalent control system is achieved. However, since the functions f and g are uncertain, the accurate equivalent control u_{eq} is difficult to reach. Here, the Takagi-Sugeno (T-S) model with constant consequents is employed to approximate u_{eq}.

Based on the principle of SMC, the control law consists of the following two parts, one is the estimated sliding component $\hat{u}_{eq}$ that is constructed by an adaptive mechanism. The function of this term is to force the system state to slide on the sliding surface. Another is the hitting control u_h that drives the states toward the sliding surface. Thus the control law can be represented as:

$$u=\hat{u}_{eq}+u_h \tag{13}$$

A. The equivalent control

In this paper, the T-S model with constant consequents is employed to approximate the equivalent control. The lth fuzzy rule is:

R_l: if S is A_1^l and $\dot{S}$ is A_2^l then $\hat{u}_{eq}$ is C_l.

Where A_1^l and A_2^l represent the fuzzy set of input variables (S, $\dot{S}$). C_l denotes constant value, l=1,2,…,L (L is number of rules). On the premise of precise attitude control, the only rules parameters C_l (l=1,2,…,L) are on-line adjusted, so as to reduce the computational burden in the control process. The output of the adaptive fuzzy controller is $\hat{u}_{eq}$.

$$\hat{u}_{eq}=C_f^T\Psi(s) \tag{14}$$

where

$$\Psi(s)=[\psi_1(s),\psi_2(s),\ldots,\psi_L(s)]^T,\ \psi_l(s)=\frac{\mu_{A_1^l}(s)\mu_{A_2^l}(\dot{s})}{\sum_{l=1}^{L}\mu_{A_1^l}(s)\mu_{A_2^l}(\dot{s})},$$

$C_f=[C_1,C_2,\cdots,C_L]^T$ is the adjustable parameter vector. $\mu_{A_1^l}$ and $\mu_{A_2^l}$ are Gaussian membership functions.

The main task of this section is to derive an adaptive law to adjust the rule parameter vector C_f such that the estimated equivalent control $\hat{u}_{eq}$ can be optimally approximated to the equivalent control of the SMC under the situations of uncertain functions f and g. Substituting (13) into (8), after some manipulations, results in:

$$e^{(n)}=r^{(n)}-f-g(\hat{u}_{eq}+u_h)-d \tag{15}$$

Substituting (11) into (15) results in:

$$e^{(n)}=gu_{eq}-\lambda_m^T\mathrm{e}-g(\hat{u}_{eq}+u_h) \tag{16}$$

(16) can be written in the following vector form:

$$\dot{\mathrm{e}}=A_c\mathrm{e}+b_c[-\hat{u}_{eq}+u_{eq}-u_h] \tag{17}$$

where

$$A_c=\begin{bmatrix}0&1&0&0&\cdots&0&0\\0&0&1&0&\cdots&0&0\\\vdots&\vdots&\vdots&\vdots&\ddots&\vdots&\vdots\\0&0&0&0&\cdots&0&1\\0&-\lambda_1&\cdots&\cdots&\cdots&\cdots&-\lambda_{n-1}\end{bmatrix},\quad b_c=\begin{bmatrix}0\\0\\\vdots\\0\\g\end{bmatrix}$$

Suppose there exists the optimal parameter vector C_f^* which is constant such that the $\hat{u}_{eq}$ has minimum approximation error $\varepsilon=\hat{u}_{eq}^*-u_{eq}$, thus:

$$\hat{u}_{eq}-\hat{u}_{eq}^*=(C_f-C_f^*)^T\Psi(s) \tag{18}$$

Define a Lyapunov function candidate:

$$V=\frac{1}{2}S^2+\frac{g}{2\gamma}\phi^T\phi \tag{19}$$

where $\phi=C_f-C_f^*$ and γ is a positive constant. Using (10) and (17) results in:

$$\dot{V}=S\dot{S}+\frac{g}{\gamma}\phi^T\dot{\phi}$$

$$=S\lambda^T A_c\mathrm{e}+gS(\hat{u}_{eq}^*-\hat{u}_{eq})-gS\varepsilon-gSu_h+\frac{g}{\gamma}\phi^T\dot{\phi}$$

$$=S\lambda^T A_c\mathrm{e}-gS(C_f-C_f^*)^T\Psi+\frac{g}{\gamma}\phi^T\dot{C}_f-gS\varepsilon-gSu_h$$

$$=-\frac{g}{\gamma}\phi^T(\gamma S\Psi-\dot{C}_f)-gS\varepsilon-gSu_h \tag{20}$$

Choosing the adaptive law $\dot{C}_f=\gamma S\Psi$, (20) becomes:

$$\dot{V}=-gS\varepsilon-gSu_h\le 0 \tag{21}$$

u_h has the same sign with Sg (refer to (24)). In order to complete the AFSMC controller design, the hitting control should be taken into account to ensure state trajectory move toward the sliding surface as well as to guarantee the stability of the control system. Achieving this goal, a Lyapunov function candidate is given as:

$$V = \frac{1}{2} S^2 \tag{22}$$

Then differentiate V with respect to time. Substituting (10) and (13) into $\dot{V}$ results in:

$$\begin{aligned} \dot{V} &= Sg[g^{-1}(\lambda_m^T e - f - d + r^{(n)}) - \hat{u}_{eq}] - Sgu_h \\ &\le |Sg|[|g^{-1}|(|\lambda_m^T e| + |f| + |d| + |r^{(n)}|) + |\hat{u}_{eq}|] - Sgu_h \end{aligned} \tag{23}$$

Choosing the hitting control

$$u_h = \mathrm{sgn}(Sg)[g_{\min}^{-1}(|\lambda_m^T e| + f_{\max} + d_{\max} + |r^{(n)}|) + |\hat{u}_{eq}|] \tag{24}$$

Thus $\dot{V} \le 0$, i.e., the hitting control actually achieves a stable fuzzy sliding mode control system.

B. The adaptive fuzzy sliding mode control law

According to (24), the hitting control u_h is usually proportional to bounds of f and g, and it is large in most of the cases. Furthermore, the sign of u_h is changed while the state trajectories across the sliding surface so that a heavily chattering phenomenon arises. This large hitting control causes high-frequency unmodelled dynamics of satellite attitude. In fact, as S is large, selecting the upper bound of f and lower bound of g is appropriate, but for small S these bounds may be unsuitable. Therefore, minimizing the hitting control should be considered in satellite attitude control. Conceptually, in sliding mode the equivalent control is described when the state trajectory is near S=0, while the hitting control is determined in the case of $S \ne 0$. Therefore, the proposed fuzzy controller design employs the expert knowledge of the sliding mode to smooth the control torque. The two heuristic fuzzy control rules are given to determine the AFSMC law u.

Rule 1 if S is ZO then u is $\hat{u}_{eq}$

Rule 2 if S is NZ then u is $\hat{u}_{eq} + u_h$

Where the fuzzy sets ZO and NZ denote zero and nonzero. The input variable S, the equivalent control $\hat{u}_{eq}$ and the hitting control u_h are given respectively in (9), (14), (24). The rule 1 states that if the value of S is zero then the control law of fuzzy controller is determined by the equivalent control $\hat{u}_{eq}$. Similarly, rule 2 states that if the value of S is nonzero then the hitting component u_h is appended to force the state trajectory moving toward the sliding surface. It is noted that the membership functions of the output variable u adopt fuzzy singleton functions. Suppose there is a crisp input S of the fuzzy controller and by the defuzzification method, the control law of the fuzzy controller is:

$$u = \frac{\mu_{ZO}(s)\hat{u}_{eq} + \mu_{NZ}(s)[\hat{u}_{eq} + u_h]}{\mu_{ZO}(s) + \mu_{NZ}(s)} = \hat{u}_{eq} + \mu_{NZ}(s)u_h \tag{25}$$

where:

$$\mu_{ZO}(s) + \mu_{NZ}(s) = 1 \tag{26}$$

The membership functions of fuzzy sets ZO and NZ are selected to be overlapped and symmetric to satisfy (26). In the satellite attitude control system, the membership functions of fuzzy sets ZO and NZ are depicted as Fig.1. It is easily known that in both regions S>0.004 and S<-0.004, the control law is the same as (13), but in other regions, the amount of hitting control is dominated by the grade of membership function of NZ. In other words, the hitting control signal could be attenuated by the grade of NZ. Furthermore, in the region $|S| \le 0.004$, it can be traded as the boundary layer of SMC.

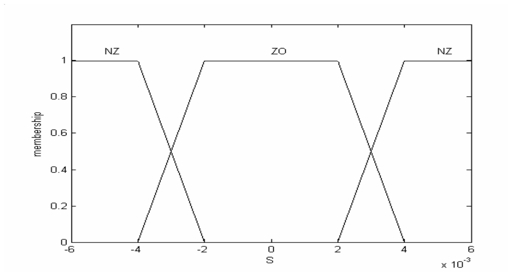


Fig. 1. The membership functions of S

As discussed above, an AFSMC has been developed to estimate the equivalent control of SMC control system. The derived adaptive law is applied to adjust the rule parameter vector C_f, so as to achieve the precise attitude control. In addition, the hitting control has also been derived to ensure the requirement of system stability. Finally, two constructed heuristic control rules are employed to smooth the control law based on the concepts of SMC.

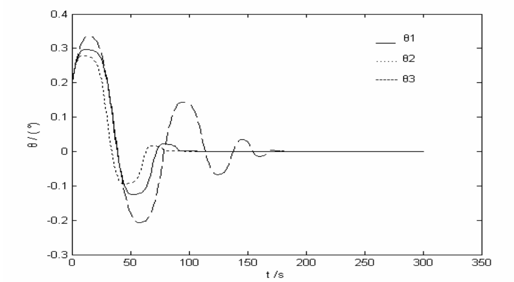
IV. SIMULATION

Three AFSMC controllers are constructed to control respectively the roll, the pitch and the yaw subsystem. The first elastic mode is considered for the simplification. The follow initial conditions are chosen as: the actual attitude $\theta_i(0) = 0.2^\circ$, $\omega_i(0) = 0.02^\circ / s$, $\eta = 0.001$, $\dot{\eta} = 0.0005$, the desired attitude $\theta_{ri} = 0^\circ$, $\omega_{ri} = 0^\circ / s$, ($i = 1, 2, 3$). The sliding surface is chosen as $S_i = 0.8e_i + \dot{e}_i$, where the error $e_i = \theta_{ri} - \theta_i$, $\dot{e}_i$ denotes the error rate. In the AFSMC, the fuzzy sets of the i-th T-S model input variables (S_i, $\dot{S}_i$) are defined as: negative big(NB), negative middle(NM), zero(E), positive middle(PM), and positive big(PB). The parameter vector C_{fi} is initialized as a linear PD controller with an acceptable performance. The initial fuzzy rules are given in Table 1. The parameter in the adaptive law is selected as $\gamma_i = 0.0003$. The hitting control u_{hi} is computed by (24). The AFSMC law u_i (i=1, 2, 3) is obtained according to (25).

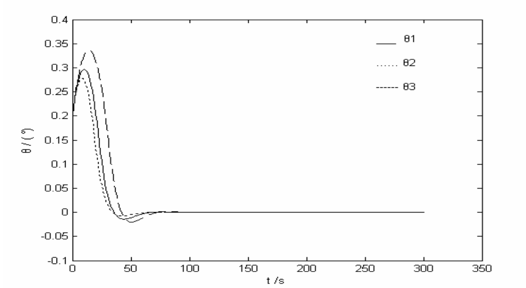
TABLE 1
THE INITIAL FUZZY RULES

$\dot{S}$ / S	NB	NS	E	PS	PB
NB	-0.2	-0.15	-0.1	-0.05	0
NS	-0.15	-0.1	-0.05	0	0.05
E	-0.1	-0.05	0	0.05	0.1
PS	-0.05	0	0.05	0.1	0.15
PB	0	0.05	0.1	0.15	0.2

The conventional sliding mode control is first constituted to make comparison with the AFSMC for the flexible satellite. The SMC law is $u_i = u_{eqi} + u_{hi}$. The equivalent control u_{eqi} is given in (11), where functions f and g are computed by using the nominal parameter of satellite, the disturbance d=0 (the unknown disturbance in advance). The hitting control u_{hi} is given in (24). Fig.2 shows the three attitude angles under the AFSMC and the SMC in the case of no external disturbance. Under the AFSMC, attitude angles converge to zero in 62s. While under the SMC, the response time is around 166s and the overshoot is bigger. It is obvious that the performance of the AFSMC is better than that of the SMC.



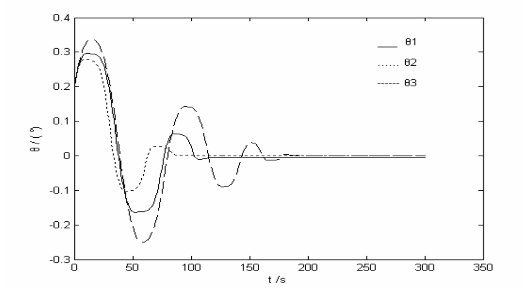
(2-a): SMC



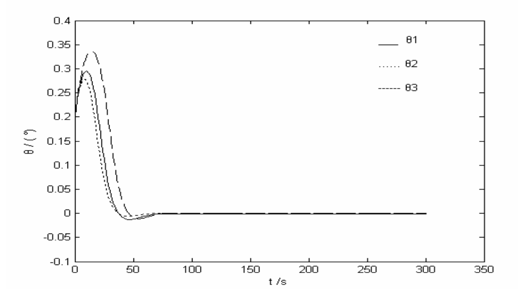
(2-b): AFSMC

Fig. 2. Attitude angles in the case of no external disturbance

To further demonstrate the robust capability of the proposed AFSMC to the external disturbance, the disturbance torque are set. Fig.3 shows the three attitude angles in the case of the external disturbance. The response time of SMC is extended to 176s, with increasing overshoot. Its error in stable state reach 0.006°. Under the AFSMC, attitude angles converge to zero in around 60s, and the error in stable state is 0.0009°. It is observed that the proposed AFSMC has superior ability to diminish the effect of both external disturbance and the disturbance caused by the panel oscillation. It is illustrated that although the SMC does have some inherent robustness to disturbance in the plant, it is not adequate; since the design is generally based on the assumption that an accurate description of satellite attitude is available.



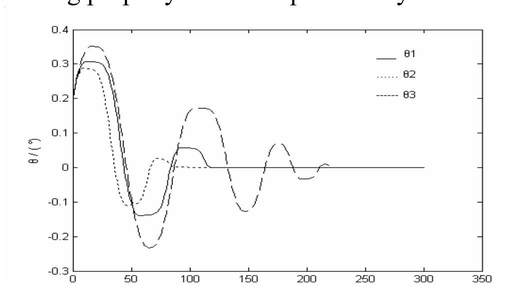
(3-a): SMC



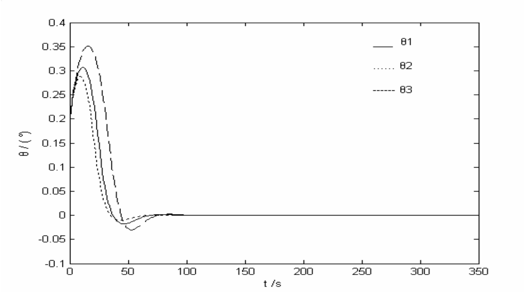
(3-b): AFSMC

Fig. 3. Attitude angles in the case of the external disturbance

In practical situation, fuel consuming, the oscillation of flexible appendages and other factors make the satellite inertia matrix not known exactly. This inertia matrix variation can heavily affect satellite attitude, which invariably present a challenge to satellite attitude control system. The following simulations demonstrate the effectiveness of the proposed AFSMC while the inertia matrix is increased to 110%J. Fig. 4-6. show the three attitude angles, modal displacement and the control torque u_1 of the roll subsystem(other two control torques are similar to control torque u_1) respectively. Under the SMC, the response time is extended to around 210s, the time of restraining the panel oscillation is longer, the chattering of control torque is observed. Under the AFSMC, the response time is around 67s, the oscillation of the solar panel attenuates to zero in about 200s, the controller produces a fairly smooth control action. This can be attributed to the interpolating property of the adaptive fuzzy control.

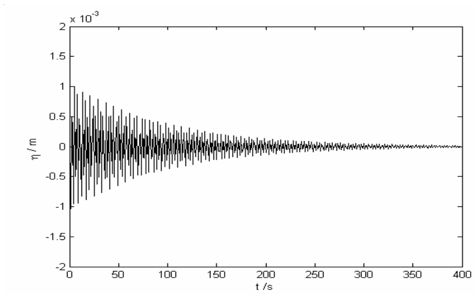


(4-a): SMC

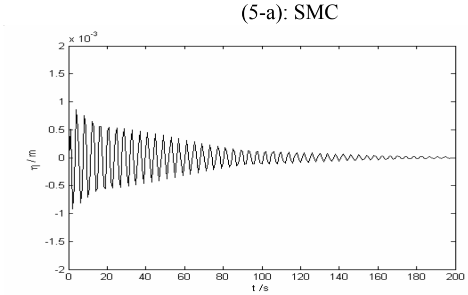


(4-b): AFSMC

Fig. 4. Attitude angles in the case of inertia matrix increment of 10%

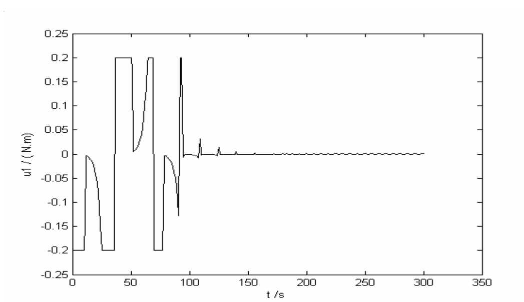


(5-a): SMC

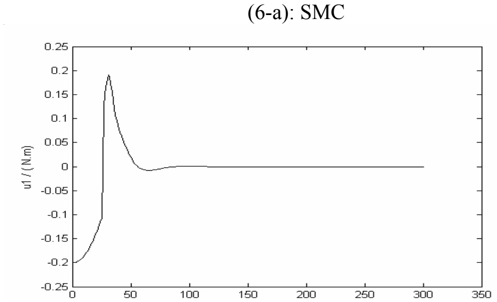


(5-b): AFSMC

Fig. 5. Modal displacement in the case of inertia matrix increment of 10%



(6-a): SMC



(6-b): AFSMC

Fig. 6. Control torque u_1 in the case of inertia matrix increment of 10%

V. CONCLUSION

The AFSMC has been successfully applied to the attitude control of flexible satellite. The fuzzy control rules of AFSMC are changed through the proposed adaptive scheme for approximating the equivalent control of SMC, thus the proposed method doesn't depend on the exact model of the controlled system. Only the rule parameter vector is on-line adjusted, leading to less computational time. In general, the hitting control need to be chosen large by the designer to ensure the stability of the control system. This induces chattering phenomenon and dissipates power in realization. Two heuristic fuzzy control rules are constructed to compensate for this drawback. Simulation results show the precise attitude control which is obtained in spit of the disturbance and uncertainties in the system, and the advantages over the conventional SMC

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