Fast Sliding Mode Control of Free-floating Flexible Space Robot by Fuzzy-based Exponential Reaching Law

*Chao Tong [1], Li Chen [2]

[1]Institute of Mechanical Engineering and Automation,Fuzhou University, Fuzhou,China, E-mail: tongchaohy@126.com

[2]Institute of Mechanical Engineering and Automation,Fuzhou University, Fuzhou,China, , E-mail: chnle@sohu.com

ABSTRACT

With the development of space technology,space robot will be more and more applied to high precision and stability task.Space robot can help installation and replacement of space station components, maintenance and recovery of failure satellites. Flexible components of space robot system, mainly the flexible manipulator and flexible joints, have not been allowed to ignore. When the free-floating flexible space robot carries out the space missions, if the manipulator produces high frequency chattering in the process of trajectory tracking control,it will reduce the service life of the robot. So the research on chattering suppression is very meaningful.

For the problem of chattering suppression in the process of trajectory tracking control by the flexible space manipulator, it discusses a method of fast sliding mode variable structure control which is based on the fuzzy exponential reaching law. Firstly, by using the Lagrange Equations of the second kind, the dynamic model of space manipulator system is established. Secondly, for improving the traditional sliding mode surface of the mechanical arm , it designs a fast nonlinear sliding mode surface, which makes its convergence speed quicker than the traditional sliding mode surface. By using fuzzy control theory, it designs a fuzzy exponential reaching law,which makes the buffeting suppression effect of the mechanical arm obvious, and guarantees the effect of trajectory tracking control of the system. It proves the stability and convergence of the system by the Lyapunov Stability Theorem.Finally, the simulation and experimental results prove the effectiveness and feasibility of the designed control method.

1 INTRODUCTION

Space manipulator plays a more and more important role in the space development process, so the study of the dynamics and control issues become the current hot spot[1].Space robot is a nonlinear, strong coupling and time-varying system, relative to the ground mechanical arm, the control technology is also more difficult and complex.Among them, the operation of the space robot with flexible manipulators is more flexible, which has attracted the interest of the researchers[2-4].It discusses the control problem of free-floating flexible space robot,when the carrier is position-uncontrolled and attitude-controlled. First, for the system,it uses the singular perturbation method[5], is decomposed into slow-varying and fast-varying subsystem.To the slow-varying subsystem, it uses the sliding mode variable structure control.To make fast convergence, it designs a fast nonlinear sliding mode. Using fuzzy theory, it designs a fuzzy exponential reaching law[7] , and guarantee its flutter suppression.To the fast-varying subsystem, using the linear quadratic optimal control[8], it makes the flexible active vibration suppression. Finally, the control algorithm is designed for the numerical simulation analysis, and the effect of this control method is verified.

2 THEORY MODEL OF SPACE ROBOT

2.1 Dynamics equation

Free-floating flexible space robot system is shown in Fig.1.Among them, O_0 coincides with O_{C0} ,the B_0 's center of mass. O_1 is the rotating hinge center with B_0 and B_1 , O_2 is the rotating hinge center with B_1 and B_2 . x_0 gets through the attachment of O_0 and O_1 , x_1 is the symmetry axis of B_1 , x_2 is the center axis when B_2 is undeformed. $\boldsymbol{e}_i$ is the based vector of $x_i(i=0,1,2)$'s direction. O_{ci} is $B_i(i=0,1,2)$'s center of mass, C is the system's center of mass. m_i is the mass of $B_i(i=0,1,2)$, M is the system's mass. I_i is $B_i(i=0,1,2)$'s moment of inertia. $\boldsymbol{r}_i$ is $B_i(i=0,1,2)$'s center-of-mass vector, $\boldsymbol{r}_c$ is the system's center-of-mass vector. l_0 is the distance of O_0 and O_1 , d_1 is the distance of O_1 and O_{c1} , l_1 is the length of B_1 , $\upsilon(x_2,t)$ is the elastic deformation of any point of flexible arm. θ_0 is the attitude angle of ontology , θ_1 and θ_2 are Joint O_1 and O_2 's relative angle.According to the Second Category of Langrange Equation,it establishes the dynamics equation of the underactuated system:

$$\boldsymbol{D}_{\delta}(\boldsymbol{q},\boldsymbol{\delta})\begin{bmatrix}\ddot{\boldsymbol{q}}\\ \ddot{\boldsymbol{\delta}}\end{bmatrix}+\boldsymbol{H}_{\delta}(\boldsymbol{q},\dot{\boldsymbol{q}},\boldsymbol{\delta},\dot{\boldsymbol{\delta}})\begin{bmatrix}\dot{\boldsymbol{q}}\\ \dot{\boldsymbol{\delta}}\end{bmatrix} +\begin{bmatrix}\boldsymbol{0}_{3\times1}\\ K_{\delta}\boldsymbol{\delta}\end{bmatrix}=\begin{bmatrix}\boldsymbol{\tau}\\ \boldsymbol{0}_{2\times1}\end{bmatrix} \tag{1}$$

In this formula, $\boldsymbol{q}=[\theta_0 \quad \theta_1 \quad \theta_2]^{\mathrm{T}}\in R^{3\times1}$ is the column vector by θ_0 、 θ_1 and θ_2 ; $\boldsymbol{\delta}=[\delta_1 \quad \delta_2]^{\mathrm{T}}\in R^{2\times1}$ is the column vector by

modal coordinates δ_1 and δ_2 ,the part of the flexible manipulator ; $\boldsymbol{D}_{\delta}(\boldsymbol{q},\boldsymbol{\delta})\in R^{5\times5}$ is the symmetric, positive definite inertia matrix of the system ; $\boldsymbol{H}_{\delta}(\boldsymbol{q},\dot{\boldsymbol{q}},\boldsymbol{\delta},\dot{\boldsymbol{\delta}})[\dot{\boldsymbol{q}}^{\mathrm{T}} \quad \dot{\boldsymbol{\delta}}^{\mathrm{T}}]^{\mathrm{T}}\in R^{5\times1}$ is the column vector Contains the coriolis force and centrifugal force; $K_{\delta}=\mathrm{diag}(\mathrm{k}_{\delta1},\mathrm{k}_{\delta2})\in R^{2\times2}$ is the stiffness coefficient matrix of the flexible arm. Among them, $\mathrm{k}_{\delta\mathrm{i}}=\int_0^{\mathrm{l}_2}\mathrm{EI}\varphi_{\mathrm{i}}''^{\mathrm{T}}\varphi''\mathrm{d}x_2 \quad (i=1,2)$; $\boldsymbol{\tau}=[\tau_0 \quad \tau_1 \quad \tau_2]^{\mathrm{T}}\in R^{3\times1}$ is the column vector by the output torque τ_0 、 τ_1 和 τ_2 .

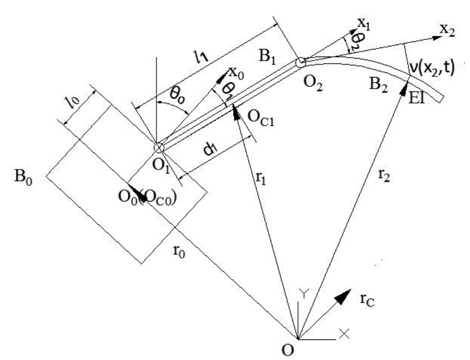

Fig 1: The free-floating flexible space robot system

2.2 Singular perturbation decomposition

Remark as:

$$\boldsymbol{D}_{\delta}(\boldsymbol{q},\boldsymbol{\delta})=\begin{bmatrix}\boldsymbol{D}_{11} & \boldsymbol{D}_{12}\\ \boldsymbol{D}_{21} & \boldsymbol{D}_{22}\end{bmatrix}$$

$$\boldsymbol{H}_{\delta}(\boldsymbol{q},\dot{\boldsymbol{q}},\boldsymbol{\delta},\dot{\boldsymbol{\delta}})=\begin{bmatrix}\boldsymbol{H}_{11} & \boldsymbol{H}_{12}\\ \boldsymbol{H}_{21} & \boldsymbol{H}_{22}\end{bmatrix}$$

$$\boldsymbol{D}_{\delta}(\boldsymbol{q},\boldsymbol{\delta})^{-1}=\begin{bmatrix}\boldsymbol{M}_{11} & \boldsymbol{M}_{12}\\ \boldsymbol{M}_{21} & \boldsymbol{M}_{22}\end{bmatrix}$$

Among them, D_{11}, H_{11}, $M_{11}\in R^{3\times3}$.

The singular perturbation scaling factor sets to $\varepsilon=\sqrt{1/\min\{K_{\delta1},K_{\delta2}\}}$,it gets a new state variables $z_{\delta}=\delta/\varepsilon^2$ and a new matrix $\overline{K}_{\delta}=\varepsilon^2 K_{\delta}$ .Then plugs in Formula (1) and get:

$$\ddot{\boldsymbol{q}}=-\boldsymbol{M}_{11}(\boldsymbol{H}_{11}\dot{\boldsymbol{q}}+\boldsymbol{H}_{12}\dot{\boldsymbol{\delta}})-\boldsymbol{M}_{12}(\boldsymbol{H}_{21}\dot{\boldsymbol{q}} +\boldsymbol{H}_{22}\dot{\boldsymbol{\delta}})-\boldsymbol{M}_{12}\overline{K}_{\delta}\boldsymbol{z}_{\delta}+\boldsymbol{M}_{11}\boldsymbol{\tau} \tag{2}$$

$$\varepsilon^2\ddot{\boldsymbol{z}}_{\delta}=\ddot{\boldsymbol{\delta}}=-\boldsymbol{M}_{21}(\boldsymbol{H}_{11}\dot{q}+\boldsymbol{H}_{12}\dot{\delta}) -\boldsymbol{M}_{22}(\boldsymbol{H}_{21}\dot{q}+\boldsymbol{H}_{22}\dot{\delta})-\boldsymbol{M}_{22}\overline{K}_{\delta}\boldsymbol{z}_{\delta}+\boldsymbol{M}_{21}\boldsymbol{\tau} \tag{3}$$

Make $\varepsilon=0$,get:

$$\overline{\boldsymbol{D}}_{11}\ddot{\boldsymbol{q}}+\overline{\boldsymbol{H}}_{11}\dot{\boldsymbol{q}}=\boldsymbol{\tau}_{\mathrm{s}} \tag{4}$$

Make $\mathrm{t_f}=\mathrm{t}/\varepsilon$, $\boldsymbol{z}_{\mathrm{f}1}=\boldsymbol{z}_{\delta}-\overline{\boldsymbol{z}}_{\delta}$ and $\boldsymbol{z}_{\mathrm{f}2}=\varepsilon\dot{\boldsymbol{z}}_{\delta}$.

By Formula (3),get:

$$\frac{\mathrm{d}\boldsymbol{Z}_{\mathrm{f}}}{\mathrm{d}\,\mathrm{t_f}}=\boldsymbol{A}_{\mathrm{f}}\boldsymbol{Z}_{\mathrm{f}}+\boldsymbol{B}_{\mathrm{f}}\boldsymbol{\tau}_{\mathrm{f}} \tag{5}$$

Among them, $\boldsymbol{Z}_{\mathrm{f}}=\begin{bmatrix}z_{\mathrm{f}1}\\ z_{\mathrm{f}2}\end{bmatrix}^{\mathrm{T}}$, $\boldsymbol{A}_{\mathrm{f}}=\begin{bmatrix}\boldsymbol{0} & \boldsymbol{I}\\ -\overline{\boldsymbol{M}}_{22}\overline{\boldsymbol{K}}_{\delta} & \boldsymbol{0}\end{bmatrix}$, $\boldsymbol{B}_{\mathrm{f}}=\begin{bmatrix}\boldsymbol{0}\\ \overline{\boldsymbol{M}}_{21}\end{bmatrix}$,

On the above formulas, the line "—" is calculated as the slow-varying time .

Then,get:

$$\boldsymbol{\tau}=\boldsymbol{\tau}_{\mathrm{s}}+\boldsymbol{\tau}_{\mathrm{f}} \tag{6}$$

3 THE CONTROLLER DESIGN

3. 1 Fast sliding mode control

The slow-varying subsystem, the rigid motion of part ,is analyzed. To compare to common sliding mode surface, convergence effect of fast terminal sliding mode surface is better. In order to improve the convergence speed, on the basis of the original, it designs a new type of fast piecewise sliding mode surface.Select displacement-tracking error of joint angle $\boldsymbol{e} = \boldsymbol{q}_{\mathrm{d}} - \boldsymbol{q}$ (among them, $\boldsymbol{q}_{\mathrm{d}}$ is the expected displacement) as the system state variable, then get the expression of sliding mode surface for mechanical arm:

$$\mathrm{s} = \begin{cases} \dot{\mathrm{e}} + \alpha \mathrm{e} + \beta \mathrm{e}^{\mathrm{p/r}}, |\mathrm{e}| \geq 1 \\ \dot{\mathrm{e}} + \alpha \mathrm{e} + \beta \mathrm{e}^{\mathrm{r/p}}, |\mathrm{e}| < 1 \end{cases} \tag{7}$$

In this formula, $\dot{\mathrm{e}}$ is the derivative of e .

The design of sliding surface determines the performance of the sliding mode motion stage, therefore, to design a suitable reaching law approach can effectively improve movement stage performance. In commonly reaching law, the effect of the exponential reaching law is better. To improve the reaching law ,use saturation function of the hyperbolic tangent function $\tanh(\mathrm{s})$ instead of sign function $\mathrm{sgn}(\mathrm{s})$, then get the expression:

$$\dot{s} = -k|s|^{\gamma} \tanh(s) \tag{8}$$

Considering two factors of converge speed and chattering inhibition,the value of γ should not be too big or small.Therefore, for the exponential reaching law, the theory of fuzzy method can be used. Under the interference, the state variables e will be changing, and the sliding surface s is the function of e , so it can measure and estimate the size of interference by the value of s . Based on the ideas, one-dimension fuzzy controller is designed, to adjust the parameters of the reaching law in real time by the size of $|\mathrm{s}|$ .And the principle is shown in Fig. 2.

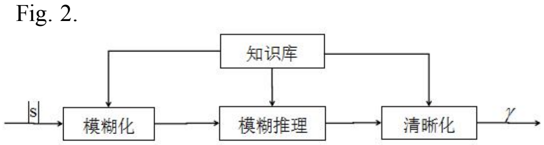

Fig 2 :The schematic diagram of controller

The design of fuzzy controller needs input variable and output variable,which can be used by the fuzzy subset described as language value as follows:

$$\{ZR, PS, PM, PB\}$$

Set the theory of domain of input variables $|\mathrm{s}|$ to be X , it can be quantified as the size of X as follows:

$$X = \{0,1,2,3,4,5\}$$

Set the theory of domain of output variables γ to be Y , it can be quantified as the size of Y like X .

Fuzzy control is one-dimensional, so use the following rule:

R_{i} : if $|\mathrm{s}|$ is A_i , then γ is B_{i} .

In this rule , A_i and B_{i} are both fuzzy sets.

Based on the experience of the control, when input variables $|\mathrm{s}|$ is large, the output variable γ is also great to inhibit the convergence rate of the input variables; when input variables is small, output variables is also small to suppress the chattering. Based on this rule, fuzzy control rule table of slow-varying subsystem is shown in table 3-1.

Table 1: Chart of the fuzzy control regularity

$\lvert S\rvert$	ZR	PS	PM	PB
γ	ZR	PS	PM	PB

The motivation methods uses MIN-MAX-GRAVITY Method, also called clear Mamdani Inference Method, and the clear control volume γ_0 is obtained. Actual control volume γ can be obtained by a scale transform from γ_0 , and the expression is shown as follows:

$$\gamma_0 = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mu_{\mathrm{B}}(\mathrm{b_i}) \cdot \mathrm{b_i}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mu_{\mathrm{B}}(\mathrm{b_i})} \tag{9}$$

In this formula, $\mu_B(\mathrm{b_i})$ is the membership degree, $\mathrm{b_i}$ is the independent variables of the membership function.

The design of the reaching law solves the problem of sliding mode switch with a strip in exponential reaching law, and ensure the converge fast.

By the derivation of Formula (7),get:

$$\dot{\boldsymbol{s}} = \ddot{\boldsymbol{e}} + \boldsymbol{g}(\boldsymbol{e}) \tag{10}$$

Among them, $\boldsymbol{g}(\boldsymbol{e})$ is shown as follows:

$$\mathrm{g}(\mathrm{e})=\begin{cases}\left(\alpha+\frac{\mathrm{p}}{\mathrm{r}}\beta(\mathrm{e})^{\mathrm{p/r\text{-}1}}\right)\dot{\mathrm{e}},|\mathrm{e}|\geq 1\\ \left(\alpha+\frac{\mathrm{r}}{\mathrm{p}}\beta(\mathrm{e})^{\mathrm{r/p\text{-}1}}\right)\dot{e},|\mathrm{e}|<1\end{cases} \tag{11}$$

Put $\boldsymbol{e}=\boldsymbol{q}_{\mathrm{d}}-\boldsymbol{q}$ plug in Formula (10),get:

$$\dot{\boldsymbol{s}}=\ddot{\boldsymbol{q}}_{\mathrm{d}}-\ddot{\boldsymbol{q}}+\boldsymbol{g}(\boldsymbol{e}) \tag{12}$$

By Formula (4) and Formula (12),get:

$$\dot{\boldsymbol{s}}=\boldsymbol{g}(\boldsymbol{e})+\ddot{\boldsymbol{q}}_{\mathrm{d}}-\overline{\boldsymbol{D}}_{11}^{-1}\left(\boldsymbol{\tau}_{\mathrm{s}}-\overline{\boldsymbol{H}}_{11}\dot{\boldsymbol{q}}\right) \tag{13}$$

By deformation, get $\boldsymbol{\tau}_{\mathrm{s}}$ as follows :

$$\boldsymbol{\tau}_{\mathrm{s}}=\overline{\boldsymbol{D}}_{11}\left\{\boldsymbol{g}(\boldsymbol{e})+\ddot{\boldsymbol{q}}_{\mathrm{d}}-\dot{\boldsymbol{s}}\right\}+\overline{\boldsymbol{H}}_{11}\dot{\boldsymbol{q}} \tag{14}$$

Among them, $\dot{\boldsymbol{s}}$ can be got by Formula (8).

Stability proof: on the sliding surface, $\mathrm{s}=0$, plug Formula (7),get:

$$\dot{\mathrm{e}}=\begin{cases}-\alpha\mathrm{e}-\beta\mathrm{e}^{\mathrm{p/r}},|\mathrm{e}|\geq 1\\ -\alpha\mathrm{e}-\beta\mathrm{e}^{\mathrm{r/p}},|\mathrm{e}|<1\end{cases} \tag{15}$$

On the sliding surface, select Lyapunov Function $V=\frac{1}{2}\mathrm{e}^2$, put Formula (8) in this formula after the derivation, get:

$$\dot{V}=\mathrm{e}\dot{\mathrm{e}}=\begin{cases}-\alpha\mathrm{e}^2-\beta\mathrm{e}\mathrm{e}^{\mathrm{p/r}},|\mathrm{e}|\geq 1\\ -\alpha\mathrm{e}^2-\beta\mathrm{e}\mathrm{e}^{\mathrm{r/p}},|\mathrm{e}|<1\end{cases} \tag{16}$$

Because $\alpha>0$, $\beta>0$ and p, q are both odd numbers,the value of $\dot{V}$ can't be a positive number,namely

$$\dot{V}\leq 0 \tag{18}$$

by the Lyapunov Stability Theory, the system is asymptotically stable after reaching the sliding surface.

3. 2 Linear quadratic optimal control design

The fast-varying subsystem, the rigid motion of part ,is analyzed. The expression of optimal control performance index function is as follows:

$$J_z=\frac{1}{2}\int_0^{\infty}(\boldsymbol{z}^T\boldsymbol{Q}_f\boldsymbol{z}+\boldsymbol{\tau}_f{}^T R_f\boldsymbol{\tau}_f)dt \tag{19}$$

Among them, the first item of the integrand is the cost function to measure the size of variable $\mathbf{z}$. The second item of the integrand means control energy consumption; $\boldsymbol{Q}_f\in R^{2\times 2}$ is a symmetric and positive semidefinite weighted matrix; $\boldsymbol{R}_f\in R^{3\times 3}$ is a symmetric and positive definite weighted matrix. The ultimate aim of optimal control is to make the value of J_z least, and its essence is to keep the system less elastic vibration and to reduce control energy consumption as possible.

According to the modern control theory, the optimal feedback control law uses the linear quadratic optimal controller (LQR) to adjust the state of the system, and make it eventually tends to zero, so as to realize the active inhibition of the system's elastic vibration. Therefore, the optimal feedback control law is designed as follows:

$$\boldsymbol{\tau}_{\mathrm{f}}=-\boldsymbol{R}_f{}^{-1}\boldsymbol{B}_{\mathrm{f}}{}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{Z}_{\mathrm{f}} \tag{20}$$

Among them, $\boldsymbol{P}$ is the unique solution of the Ricatti Equation, and it is shown as follows:

$$\boldsymbol{P}\boldsymbol{A}_{\mathrm{f}}+\boldsymbol{A}_{\mathrm{f}}{}^{\mathrm{T}}\boldsymbol{P}-\boldsymbol{P}\boldsymbol{B}_{\mathrm{f}}\boldsymbol{R}^{-1}\boldsymbol{B}_{\mathrm{f}}\boldsymbol{P}+\boldsymbol{Q}_{\mathrm{f}}=\boldsymbol{0} \tag{21}$$

4 SIMULATION RESEARCH

As shown in Fig.1, the numerical simulation experiment of free-floating flexible space robot system is carried out. Inertia parameters of the system are design as follows:

$\mathrm{m}_0=40\mathrm{kg}$, $\mathrm{m}_1=2\mathrm{kg}$; $l_0=1.5\mathrm{m}$, $l_1=3\mathrm{m}$, $l_2=3\mathrm{m}$, $d_1=1.5\mathrm{m}$; $I_0=34.17\mathrm{kg}\cdot\mathrm{m}$, $I_1=3\mathrm{kg}\cdot\mathrm{m}$; $\rho=1\mathrm{kg/m}$, $EI=300N\cdot\mathrm{m}^2$.

The controller parameters are shown as follows:

$\alpha=1$, $\beta=1$, $\mathrm{k}=5$, $\mathrm{r}=5$, $\mathrm{p}=7$.

Assume the expected trajectory of carrier attitude angle and the joint angles are shown as follow:

$$\theta_{0\mathrm{d}}=0$$

$$\theta_{1\mathrm{d}}=\frac{\pi}{4}\left(\frac{t}{8}-\frac{1}{2\pi}\sin\left(\frac{\pi t}{5}\right)\right)$$

$$\theta_{2\mathrm{d}}=\frac{\pi}{4}\left(1-\frac{t}{8}+\frac{1}{2\pi}\sin\left(\frac{\pi t}{5}\right)\right)\ (\mathrm{rad})$$

The initial value of the system is shown as follow:

$\theta_0(0)=0.1\mathrm{rad}$, $\theta_1(0)=0.05\mathrm{rad}$,

$\theta_2(0) = 0.95\text{rad}$, $\delta_1 = 0$, $\delta_2 = 0$;

$\dot{\theta}_0(0) = \dot{\theta}_1(0) = \dot{\theta}_2(0) = 0$, $\dot{\delta}_1 = 0$, $\dot{\delta}_2 = 0$.

The whole process lasts for 20 s.

The simulation results are shown in Fig.3,Fig.4,Fig.5,Fig.6,Fig.7 and Fig.8.

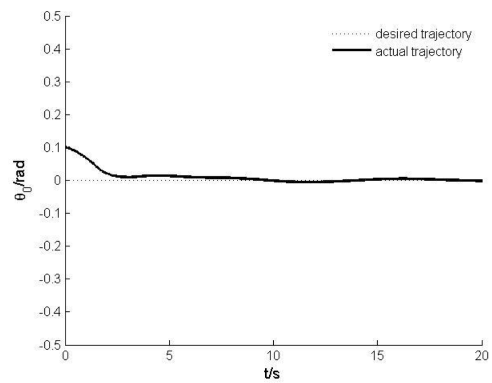

Fig 3 :Trajectory tracking of attitude angle θ_0

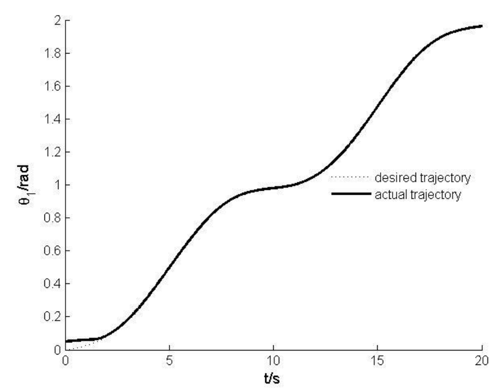

Fig 4 :Trajectory tracking of joint angle θ_1

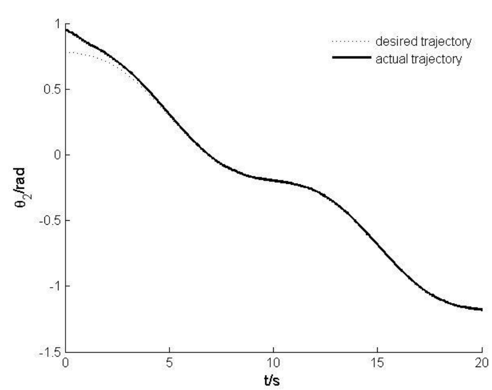

Fig 5 :Trajectory tracking of joint angle θ_2

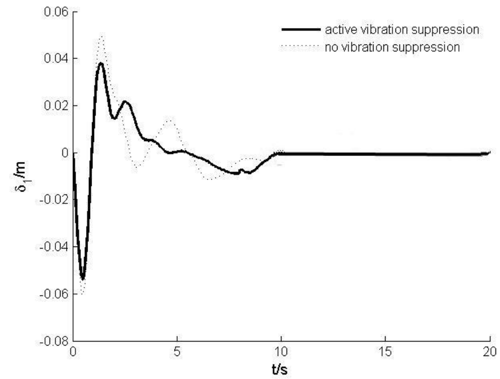

Fig 6 :Trajectory tracking of first-order modal δ_1

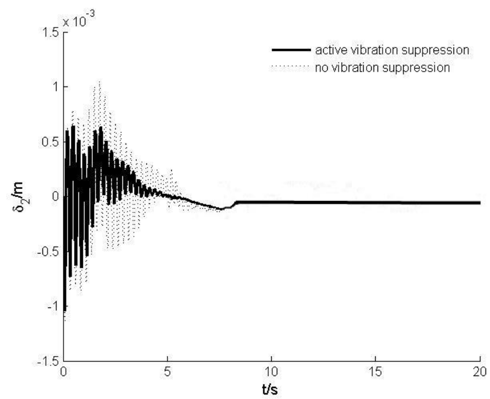

Fig 7 :Trajectory tracking of second-order modal δ_1

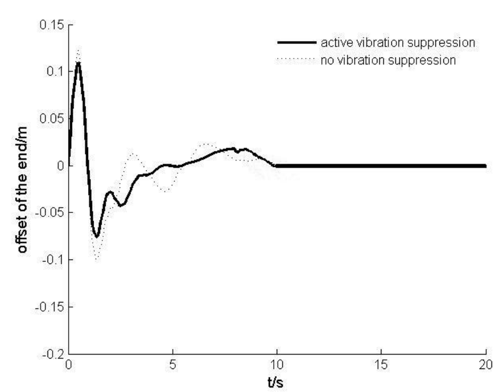

Fig 8 :Trajectory tracking of offset at the end

The simulation results show that the design of the compound control scheme guarantees the hinge joints to track the desired trajectory quickly and steadily, also realizes the flexible active vibration suppression.

5 CONCLUSION

Fast sliding mode control by fuzzy-based exponential law is applied to the control of free-floating flexible space robot. The designed control scheme guarantees hinge joints to track the desired trajectory quickly and steadily, and the flexible vibration suppression is realized. The simulation results prove the feasibility and the effectiveness of the proposed control scheme.

Appendix

ρ : the linear density of the flexible manipulator.

EI :the bending stiffness of the flexible manipulator.

Acknowledgement

This work was supported by'Natural Science Foundation of China(11372073)'.The Scientific research condition was provided by Fuzhou University.We also thank Professor Li Chen for providing help.

References

[1] Lindsay Evans (2005) Canadian space robotics on board the international space station//2005 CCToMM Symposium on Mechanisms, Machines, and Mechatronics. Montreal: Canadian Space Agency.

[2] Kumar A, Pathak P M, Sukavanam N (2011) Reduced model based control of two link flexible space robot. Intelligent Control and Automation, 2(02): 112-120.

[3] Licheng Wu, Fuchun Sun, Zengqi Sun, et a1 (2002) Dynamic modeling, control and simulation of flexible dual-arm space robot, Proceeding of IEEE Region 10 Conference Computers, Communications, Control and Power Engineering. Beijing, China, pp.l282-1285.

[4] Zhaobin Hong, Li Chen (2009) Hybrid control scheme of coordinated motion and active vibration control for a free-floating space flexible manipulator with parameter uncertainty. Journal of Vibration and Shock, 29(11):94-99.

[5] Kejian Zeng, Guang Li (2006) Singular Perturbation Control Approach to a Hydraulically Driven Flexible Manipulator. China Mechanical engineering, 17(11):1128-1131.

[6] Leiping Xi, Zili Chen and Xiaohui Qi (2012) Fast sliding mode variable structure control for manipulators with chattering suppression effect. Electric Machines and Control, 16(7):97-102.

[7] Hong Mei, Yong Wang (2009) Fast Convergent Sliding Mode Variable Structure Control of Robot. Information and Control, 38(5):552-557.

[8] Yanding Wei, Junqiang Lou a, Yonggui Lv,et al (2009) Research on linear quadratic optimal control problem in active vibration control. Journal of Zhejiang University(Engineering Science), 43(3): 420-424.

[9] Qiming Liu (2004) Design of Fuzzy Reach Law of Sliding-mode Control. Journal of Fudan University, 43(5): 952-955.