Dual adaptive control of mechanical arm

Bingtao Lu, Jiexin Pu, Jing Liu

Abstract—**Aiming at the frictional force and the modeling error caused by the change of model parameters in joint robot control system, the design method of dual adaptive controller is discussed in this paper. The uncertain dynamics caused by the change of the parameters of the robot model is compensated by the adaptive controller composed of the regression matrix. At the same time, Adaptive fuzzy control algorithm is used to overcome the friction of robot joints, Lyapunov function is used to determine the adaptive laws the method ensures global stability of the system, The simulation results show that the controller has a good position and speed tracking ability in the presence of model error and friction interference.**

Keywords—Robotic manipulator; trajectory tracking; fuzzy adaptive chattering

I. INTRODUCTION

Robot manipulators play a significant role in automation. They have been widely used in various applications where many tasks require high-speed and high-precision trajectory tracking. However, robotic manipulators generally face many uncertainties and external disturbances in their dynamics, such as payload variations, frictions, external disturbances, and sensor noises. Thus, the control of robot manipulators is a hot topic in the domain of control. The traditional linear control cannot get the ideal control effect due to the weak robustness and low control precision, so some intelligent control strategies are applied to the control of the manipulator

At present, many literatures have studied the control of manipulator, various control approaches that attenuate the effect of robotic uncertainties have been proposed, such as fuzzy control, robust adaptive control, sliding mode control, and neural network control. Literature [1-3] shows the robust control of the mechanical arm can guarantee the overall stability of the system, but it affects the real-time engineering application. Literature [4-8] used the universal approximation feature of the fuzzy system to realize the approximation of the uncertainty; Fuzzy approximation is a better way to deal with uncertainty. The more the precision of fuzzy approximation is, the more fuzzy rules are, Therefore, the problem of high dimension of fuzzy system is very widespread.

Literature [9] used adaptive robust control method to overcome the effects of uncertainty; the controller has a strong robustness, but robust control is a very conservative controller and its stability in most cases is guaranteed by the sacrifice of dynamic performance.

In this paper, the dual adaptive controller is designed for the modeling error and friction interference of the manipulator. Adaptive fuzzy control is used to compensate the influence of friction on the system; the adaptive control learning algorithm based on the regression matrix to overcome the modeling error caused by the variation of robot model parameters. We provide the detailed control algorithm. Finally, the simulation results show the effectiveness of the proposed method

II. PROBLEM DESCRIPTION

Considering an n-link robot, its dynamic performance is described by the following second-order nonlinear differential equation.

$$D(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)+F(\dot{q})=\Gamma \tag{1}$$

where $q,\dot{q},\ddot{q}\in R$ are the joint position, velocity, and acceleration vectors, respectively; $D(q)\in R^{n\times n}$ is the bounded positive-definite inertia matrix; $C(q,\dot{q})\in R^{n\times n}$ is the matrix of coriolis and centrifugal forces; $G(q)\in R^{n}$ is the gravity vector; $F(\dot{q})\in R^{n}$ is the interference term of friction， $T\in R^{n}$ is the vector of the control input for the robot;

For robot systems, some dynamics characters are shown below:

Character 1: The inertial matrix $D(q)$ is the positive definite matrix and bounded,

Character 2: $\dot{D}(q)-2C(q,\dot{q})$ is a skew symmetric matrix, for any vector that have:

$$\chi^{T}(\dot{D}(q)-2C(q,\dot{q}))\chi=0 \tag{2}$$

Character 3; with the proper selection of physical parameters such as length, mass and inertia matrix of robot, there exists a parameter vector dependent on the manipulator to make $D(q),C(q,\dot{q})$ and $G(q)$ satisfy the linear relationship

$$\tilde{D}(q)\ddot{q}_r+\tilde{C}(q,\dot{q})\dot{q}_r+\tilde{G}(q)=\tilde{Y}(q,\dot{q},\dot{q}_r,\ddot{q}_r)\tilde{a} \tag{3}$$

Where $\tilde{Y}(q,\dot{q},\dot{q}_r,\ddot{q}_r)\tilde{a}$ is the regression matrix of known joint variable functions，It is a known function matrix of the generalized coordinates of the robot and its derivatives. $\tilde{a}\in R^{n}$ is an unknown definite constant parameter vector describing the quality characteristics of a robot. This equation can be used to separate the unknown parameters in

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the robot dynamics equation, and to deal with the uncertain parameters of the robot.

III. DSIGNE OF CONTROL

The desired position of the robots joints is defined q_d

Thus the position tracking error is: $e = q - q_d$

Lets $\dot{q}_r = \dot{q}_d - \Lambda e \quad \ddot{q}_r = \ddot{q}_d - \Lambda \dot{e}$

The sliding surface is defined as:

$$s = \dot{q} - \dot{q}_r = \dot{q} - (\dot{q}_d - \Lambda e) = \Lambda e + \dot{e}$$

The control moment is designed as

$$\Gamma = \hat{D}(q)\ddot{q}_r + \hat{C}(q,\dot{q})\dot{q}_r + \hat{G}(q) + \hat{F}(\dot{q} \mid \Theta) - K_D S \quad (4)$$

Where $K_D = disg(K_i) \quad K_i > 0 \; , i = 1,2,....,n,$

If the system does not exist external model deviation, load and friction interference, selecting different control gain can achieve the purpose of convergence. But in practical engineering, there are various perturbations; some traditional control methods can't meet the requirements of control accuracy and stability. The sliding mode control (SMC) is one of the influential nonlinear control methods that have been widely applied to control both certain and uncertain systems. The SMC has the advantages of simple control, quick response, easy implementation, descending order and decoupling. Thus, the SMC is also commonly used to control robotic manipulators. To make full use of advantages of sliding mode controller; this article is based on this, the uncertain model error is compensated by the adaptive controller composed of the regression matrix and the friction of the manipulator is compensated by adaptive fuzzy compensator. Fuzzy control not only can realize the approximation to arbitrary non-linear function also can greatly reduce the chatting of sliding mode.

IV. DSIGNE OF FUZZY RULES

Since friction is only related to speed, $\dot{q}_i (i = 1,2,..,n)$ is used as fuzzy control input, to define 5 fuzzy sets, and the fuzzy system is designed:

$$\hat{F}(\dot{q} \mid \Theta) = \begin{bmatrix} \hat{F}_1(\dot{q}_1 \mid \Theta_1) \\ \hat{F}_2(\dot{q}_2 \mid \Theta_2) \\ \vdots \\ \hat{F}_n(\dot{q}_n \mid \Theta_n) \end{bmatrix} = \begin{bmatrix} {\Theta_1}^T \varepsilon^1(\dot{q}_1) \\ {\Theta_2}^T \varepsilon^2(\dot{q}_2) \\ \vdots \\ {\Theta_n}^T \varepsilon^n(\dot{q}_n) \end{bmatrix}$$

Where $\varepsilon(q)$ is the $\prod_{i=1}^{n} m_i$ dimension vector, and $l_1,...,l_n$ are respectively:

$$\varepsilon_{l_i,...,l_n}(\dot{q}) = \frac{\prod_{i=1}^{n} \mu_{A_i^{l_i}}(\dot{q}_i)}{\sum_{l_1=1}^{m_1} \cdots \sum_{l_n=1}^{m_n} \left(\prod_{i=1}^{n} \mu_{A_i^{l_i}}(\dot{q}_i) \right)}$$

Where $\mu_{A_i^{l_i}}(\dot{q}_i)$ is the membership function, $\dot{q}_i$ are the input variables of the fuzzy controller, ε_i are the output variables, the subsets of the input and output variables are described as $\{NB \quad NS \quad O \quad PS \quad PB\}$, fuzzy control rules are:

IF $\dot{q}_i$ is A_i , THEN ε_i is B_i

Where A_i and B_i are fuzzy set, Using the above fuzzy control rule $\hat{F}$ can be adjusted in real time to realize the fuzzy approximation of $F(\dot{q})$.

Define the following variables

$$\Theta^* = \arg\min \{ \sup | F(\dot{q}) - F(\dot{q} \mid \Theta) | \}$$

$$\tilde{\Theta} = \Theta^* - \Theta$$

$$w = F(\dot{q}) - \hat{F}(\dot{q} \mid \Theta^*) \quad (4)$$

Where, Θ^* is the optimal approximation parameter is: $\tilde{\Theta}$ is the parameter approximation error, and ω is the least fuzzy approximation error.

Fuzzy adaptive law is designed as:

$$\Theta_i = -\lambda_i^{-1} s_i \varepsilon(\dot{q}) \quad (5)$$

V. LYAPUNOV FUNCTION DESIGN

Considering the fuzzy approximation and estimation parameter error，The Lyapunov function is defined as：

$$V = \frac{1}{2} S^T D S + \frac{1}{2} \tilde{a}^T \tau_1 \tilde{a} + \frac{1}{2} \sum_{i=1}^{n} \tilde{\Theta}_i^T \lambda_i \tilde{\Theta}_i \quad (6)$$

Where $\tilde{\Theta} = \Theta^* - \Theta$ ， $\tilde{a} = \hat{a} - a$ ，are parameter estimation errors， Θ^* is the ideal parameter， a is a constant vector， τ_1 and λ_i are greater than zero；

Then, the derivative of V becomes

$$\dot{V}(t) = S^T D \dot{S} + \frac{1}{2} S^T \dot{D} S + \tilde{a}^T \tau_1 \dot{\tilde{a}} + \sum_{i=1}^{n} \tilde{\Theta}_i \lambda_i \dot{\tilde{\Theta}}_i$$

$$\dot{V}(t) = S^T D(\ddot{q} - \ddot{q}_r) + \frac{1}{2} S^T \dot{D} S + \tilde{a}^T \tau_1 \dot{\tilde{a}} + \sum_{i=1}^{n} \tilde{\Theta}_i \lambda_i \dot{\tilde{\Theta}}_i \quad (7)$$

Applying (1) and (4) into (6) yields;

$$\dot{V}(t) = S^T (\hat{D}\ddot{q}_r + \hat{C}\dot{q}_r + \hat{G} + \hat{F}(\dot{q} \mid \Theta) - K_D S - C(q,\dot{q})(S + \dot{q}_r)$$
$$-G(q) - F(\dot{q}) - D\ddot{q}_r) + \frac{1}{2} S^T \dot{D} S + \tilde{a}^T \tau_1 \dot{\tilde{a}} + \sum_{i=1}^{n} \tilde{\Theta}_i \lambda_i \dot{\tilde{\Theta}}_i \quad (8)$$

Lets $\tilde{D} = \hat{D} - D, \tilde{C} = \hat{C} - C, \tilde{G} = \hat{G} - G$

Thus

$$\dot{V}(t) = S^T (\tilde{D}\ddot{q}_r + \tilde{C}\dot{q}_r + \tilde{G} - K_D S + \hat{F}(\dot{q} \mid \Theta) - F(\dot{q})$$
$$-C(q,\dot{q})S) + \frac{1}{2} S^T \dot{D} S + \tilde{a}^T \tau_1 \dot{\tilde{a}} + \sum_{i=1}^{n} \tilde{\Theta}_i \lambda_i \dot{\tilde{\Theta}}_i \quad (9)$$

According to the linear nature of the robot:

Substituting (4) into (9) yields

$$\dot{V}(t) = -S^T K_D S + S^T (\tilde{Y}(q,\dot{q},\dot{q}_r,\ddot{q}_r)\tilde{a}) + S^T (\hat{F}(\dot{q} \mid \Theta) - F(\dot{q}))$$
$$+ \tilde{a}^T \tau_1 \dot{\tilde{a}} + \sum_{i=1}^{n} \tilde{\Theta}_i \lambda_i \dot{\tilde{\Theta}}_i \quad (10)$$

In order for the controller to be globally stable, $\dot{V}$ must satisfy the condition that $\dot{V}(t) \le 0$

Thus let

$$S^T (\tilde{Y}(q,\dot{q},\dot{q}_r,\ddot{q}_r)\tilde{a}) + \tilde{a}^T \tau_1 \dot{\tilde{a}} = 0 \quad (11)$$

From (11), we can obtain

$$\dot{\hat{a}} = -\tau_1 \tilde{Y}^T(q,\dot{q},\dot{q}_r,\ddot{q}_r)s \qquad (12)$$

So

$$\dot{V}(t) = = -S^T K_D S + S^T(\hat{F}(\dot{q}\mid\Theta) - F(\dot{q})) + \sum_{i=1}^{n} \tilde{\Theta}_i \lambda_i \dot{\tilde{\Theta}}_i \qquad (13)$$

Let

$$\dot{V}_1(t) = S^T(\hat{F} - F(\dot{q}\mid\Theta)) + \sum_{i=1}^{n} \tilde{\Theta}_i \lambda_i \dot{\tilde{\Theta}}_i$$

Thus

$$\dot{V}_1(t) = S^T(\hat{F}(\dot{q}\mid\Theta) + \hat{F}(\dot{q}\mid\Theta^*) - \hat{F}(\dot{q}\mid\Theta^*) - F(\dot{q})) + \sum_{i=1}^{n} \tilde{\Theta}_i \lambda_i \dot{\tilde{\Theta}}_i$$

$$\dot{V}_1(t) = -S^T w + S^T(\hat{F}(\dot{q}\mid\Theta) - \hat{F}(\dot{q}\mid\Theta^*)) + \sum_{i=1}^{n} \tilde{\Theta}_i \lambda_i \dot{\tilde{\Theta}}_i$$

$$\dot{V}_1(t) = -S^T w + \sum_{i=1}^{n} (\tilde{\Theta}_i \lambda_i \dot{\tilde{\Theta}}_i - s_i \tilde{\Theta}_i^T \varepsilon(\dot{q}) \qquad (14)$$

From (4) , we have

$$\dot{V}(t) = -S^T K_D S - S^T w \le 0 \qquad (15)$$

In order to reduce the influence of fuzzy approximation error, the robust term is added in the control law, and the symbol function is replaced by tan-h function to weaken the chattering caused by sliding mode.

$$\tanh(s) = \frac{\exp(s) - \exp(-s)}{\exp(s) + \exp(-s)}$$

So we design the following controllers:

$$\Gamma = \hat{D}(q)\ddot{q}_r + \hat{C}(q,\dot{q})\dot{q}_r + \hat{G}(q) + \hat{F}(\dot{q}\mid\Theta) - K_D S - W\tanh(s)$$

VI. Simulation Examples

Consider the two-link manipulators. The structure of the joint manipulator is shown in fig 1.

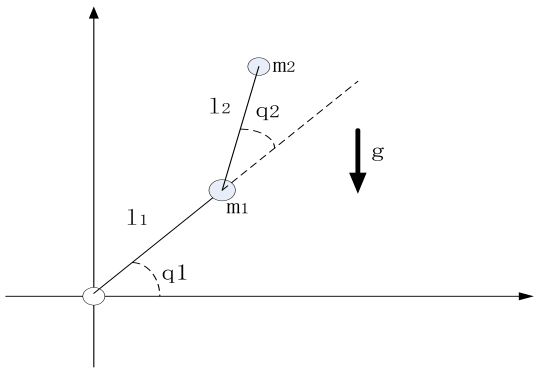

Fig. 1 two joints mechanical arm structure

The dynamical equation of the manipulators is:

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau + d$$

Where

$$D(q) = \begin{bmatrix} \alpha + 2\varepsilon\cos(q_2) + 2\eta\sin(q_2) & \beta + \varepsilon\cos(q_2) + \eta\sin(q_2) \\ \beta + \varepsilon\cos(q_2) + \eta\sin(q_2) & \beta \end{bmatrix}$$

$$C(q,\dot{q}) = \begin{bmatrix} (-2\varepsilon\sin(q_2) + 2\eta\cos(q_2))\dot{q}_2 & (-\varepsilon\sin(q_2) + \eta\cos(q_2))\dot{q}_2 \\ (\varepsilon\sin(q_2) - \eta\cos(q_2))\dot{q}_1 & 0 \end{bmatrix}$$

$$G(q) = \begin{bmatrix} \varepsilon e_2\cos(q_1+q_2) + \eta e_2\sin(q_1+q_2) + (\alpha - \beta + e1)e_2\cos(q_1) \\ \varepsilon e_2\cos(q_1+q_2) + \eta e_2\sin(q_1+q_2) \end{bmatrix}$$

where

$$\alpha = I_1 + m_1 l_{c1}^2 + I_e + m_e l_{ce}^2 + m_e l_1^2,$$

$$\beta = I_e + m_e l_{ce}^2 ,$$

$$\varepsilon = m_e l_e l_{ce}\cos(\delta) ,$$

$$\eta = m_e l_1 l_{ce}\sin(\delta)$$

Here, $m_1 = 1kg$, $l_1 = 1$, $l_{c1} = 0.5$, $I_1 = 1/12$, $m_e = 3$, $I_{ce} = 1$, $I_e = 0.4$, $\delta_e = 0$, $e_1 = -7/12$, $e_2 = 9.81$ The desired joint trajectories for tracking are

$$q_{d1} = \sin(t)$$

$$q_{d2} = \sin(t)$$

The initial value of the accused object is:

$$[q_{d1}, \dot{q}_{d1}, q_{d2}, \dot{q}_{d2}]^T = [0.5, 0, 0.5, 0]^T$$

The estimation friction signal of the two joints is:

$$F(\dot{q}) = \begin{bmatrix} 0.5\dot{q}_1 + 0.2{*}\mathrm{sign}(\dot{q}_1) & 0.5\dot{q}_2 + 0.2\mathrm{sign}(\dot{q}_2) \end{bmatrix}$$

Taking the following five membership functions:

$\mu_{NB} = \exp[-((x_i + pi/6)/(pi/24))\hat{}2]$

$\mu_{NS} = \exp[-((x_i + pi/12)/(pi/24))\hat{}2]$

$\mu_{O} = \exp[-(x_i/(pi/24))\hat{}2]$

$\mu_{PS} = \exp[-((x_i - pi/12)/(pi/24))\hat{}2]$

$\mu_{PB} = \exp[-((x_i - pi/6)/(pi/24))\hat{}2]$

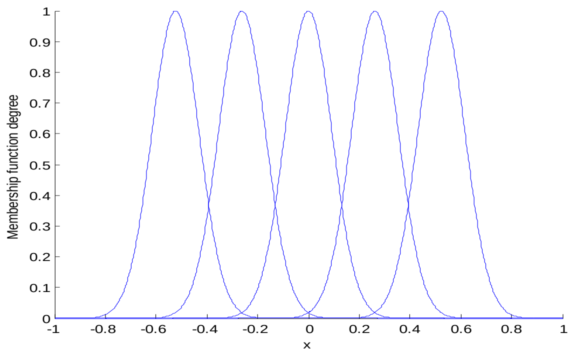

Fig. 2 Membership function graph

The simulation results of double adaptive algorithm in this paper are as follows. Figures 3-6 show the position tracking, position tracking error, velocity tracking and velocity tracking error of two joints, which show that the proposed method is effective.

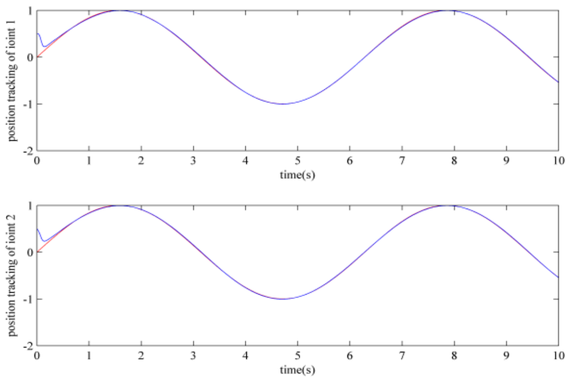

Fig. 3 Position tracking curves of two joints

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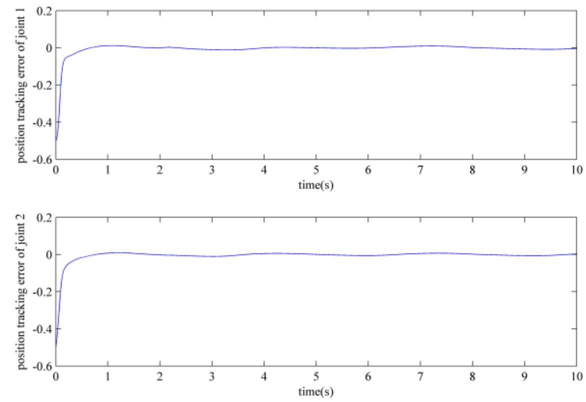

Fig. 4 Position tracking error curves of two joints

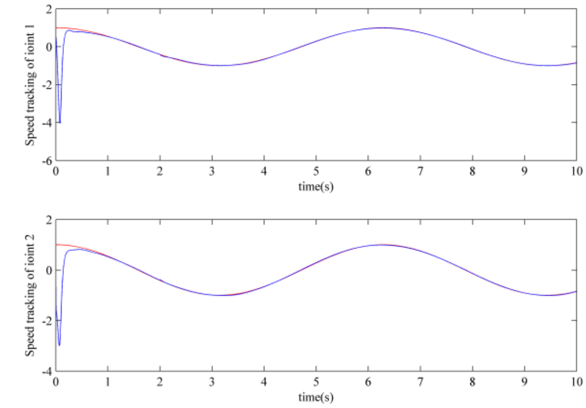

Fig. 5 Velocity tracking curves of two joints

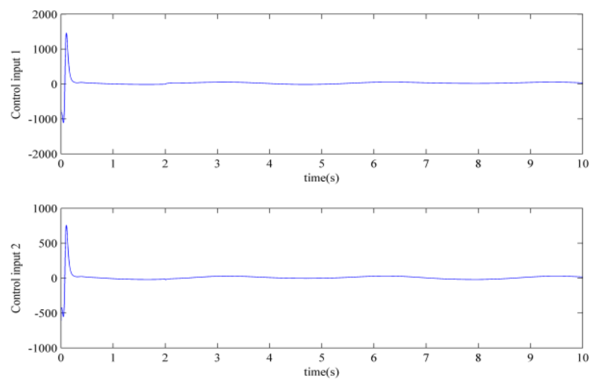

Fig. 6 Control input curves of two joints

To present the advantages of the proposed method, we compare the results in figure 3-6 with the simulation results of the computed torque control, as shown in figures 7-10

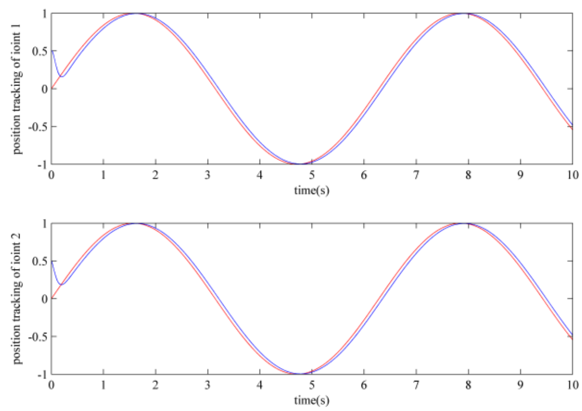

Fig. 7 Position tracking curves of two joints

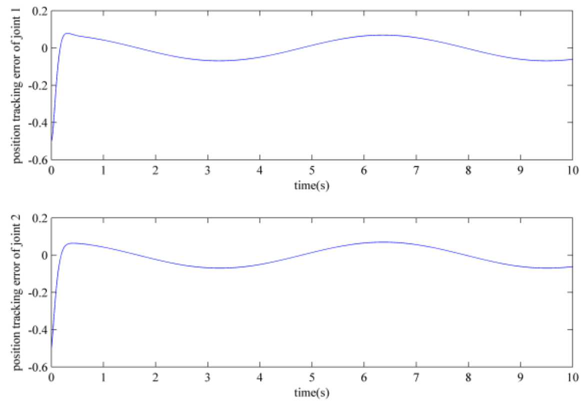

Fig. 8 position tracking error curves of two joints

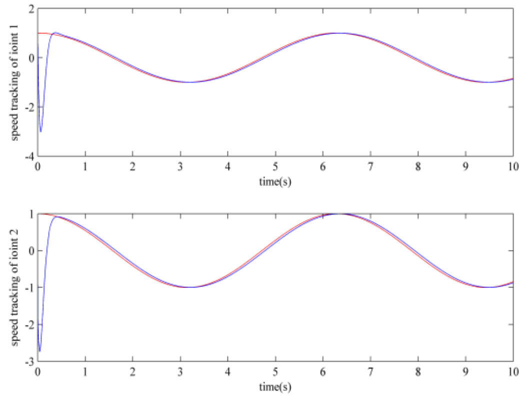

Fig. 9 Velocity tracking curves of two joints

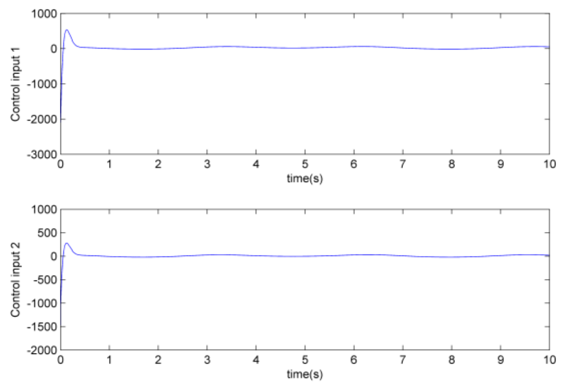

Fig. 10 Control input curves of two joints

The simulation results are obviously better than the fuzzy adaptive control after the double adaptive control is adopted in this paper; the position and velocity tracking errors of the proposed method can also more rapidly converge to zero。The control performance of the system is improved.

VII. CONCLUSITION

The dual adaptive controller is designed in this paper. The relative variables of robot structure are approximating with adaptive law, and the nonlinear friction volume of robot is compensated by adaptive fuzzy control law. The experimental results show that the dual adaptive control law not only has a fast convergence speed and tracking accuracy, but also can effectively suppress the vibration of the system, so it has better control performance.

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