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FINITE TIME COMMAND FILTERED ADAPTIVE FUZZY CONTROL FOR A TWIN ROLL INCLINED CASTING SYSTEM

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This paper, the adaptive fuzzy control problem for finite-time command filtering is studied at the twin roll inclined casting system. An explosion of complexity caused by a differential surge can be avoided by constructing adaptive fuzzy controller combined with command filtering and backstepping schemes. The designed adaptive fuzzy controller ensures simultaneously the stability and tracking performance of the closed-loop system in a limited time, and the tracking error converges in a small neighborhood of the origin. Eventually, a simulation example is given to verify the effectiveness of the proposed scheme.

Key words: twin roll, inclined casting system, finite time, command filter, fuzzy control

INTRODUCTION

Twin roll casting is a combination of casting and rolling, which has the advantages of reducing cost, saving energy, rapid cooling, and so on, and can significantly improve the microstructure and properties of metals, so it has attracted much attention from scholars at home and abroad. Compared with horizontal system, the twin roll inclined casting can reduce specific gravity segregation and Increase casting speed [1,2].

On the basis of that, Zhang systematically studied the equal-diameter twin-roll inclined casting process in terms of theoretical model, numerical simulation and process control [3,4], and as seen in [3], a single input single output (SISO) non-affine nonlinear mathematical model is established for twin-roll inclined casting process, and a novel adaptive fuzzy controller is devised based on fuzzy approximation technology for decoupling to achieve the objective of controlling the liquid level reasonably. But there are two major problems with the above control methods. Firstly, above-mentioned method can only guarantee stability at infinite time. Nevertheless, in industrial applications, it is universally acknowledged that finite time controllers are one of the most effective methods to drive the system trajectory to converge to equilibrium in a finite number of steps. Then constant differentiation of virtual control inputs leads to an explosion of complexity, and on condition that the dimensions of the system are too high, it will hinder its wider application. Accordingly, this problem can be shunned by introducing the command filter in the backstepping design. An adaptive fuzzy finite time control scheme for nonlinear systems is presented in [5,6]. In [7,8], an adaptive command filtering backstepping control method for a class of nonlinear systems is described. Based on these results, this paper studies the adaptive fuzzy control of finite time command filter for twin roll inclined casting system.

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TWIN ROLL INCLINED CASTING SYSTEM MODEL

The following twin roll inclined casting nonaffine nonlinear system is constructed by introducing coordinate transformation.

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \tau u + f(x, \beta, u) \\ y = x_1 \end{cases} \tag{1}$$

where $x = [x_1, x_2]^T$ is state vector, u is control input, y is output of the system. The twin roll inclined casting schematic diagram is shown in Figure 1.

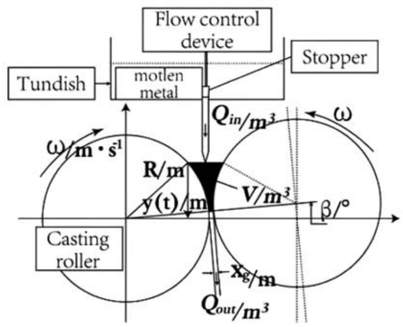

Figure 1 Schematic view of the twin-roll inclined casting with an inclined angle

Assumption 1: For the above system, there are unknown positive constants $\overline{A}_1$ and $\overline{A}_2$, such that $y_r \le \overline{A}_1$, $\dot{y}_r \le \overline{A}_2$.

Definition 1: Consider the following nonlinear system:

$$\dot{x} = f(x,\overline{u}),\ f(0,0) = 0,\ x \in R^n, \overline{u} \in R^n \tag{2}$$

where x is the state vector and $\overline{u}$ is the input vector; $f : D \rightarrow R^n$ is continuous on an open neighborhood D around the origin. The origin of system (2) is semiglobal practical finite-time stability, if for every initial condition $x(t_0) = x_0$, there exists $\rho > 0$ and a setting time $0 < T(x_0, \rho) < \infty$ such that $\|x(t)\| \le n$ for all $t \ge t_0 + T$.

Lemma 1 [7]**:** If there exist some design constants a, $b > 0$, $0 < p < 1$, $0 < c < \infty$ such that

$$\dot{V}(x) \le -aV(x) - bV^p(x) + c \tag{3}$$

then the trajectory of system $\dot{x} = f(x,u)$ is practical finite time stable.

Lemma 2: The fuzzy logic system (FLS) can uniformly approximate the continuous nonlinear function $f(x)$ with arbitrary precision on the compact set Ω_x as follows

$$f(x) = \theta^T \phi(x) + \varepsilon(x) \tag{4}$$

where $x \in \Omega_x$, $\varepsilon(x)$ is approximate error, and satisfy $|\varepsilon(x)| < \varepsilon$, θ^* is a given ideal parametric regression vector, can be expressed as

$$\theta^* = \arg\min_{\theta \in \Omega_\theta} \{\sup_{x \in \Omega_x} |f(x) - \theta^T \phi(x)|\} \tag{5}$$

Lemma 3 [8]**:** The command filter is defined as

$$\begin{aligned} \dot{\varphi}_1 &= w_n \varphi_2 \\ \dot{\varphi}_2 &= -2\zeta w_n \varphi_2 - w_n(\varphi_1 - \alpha_1) \end{aligned} \tag{6}$$

If the input signal α_1 satisfies $|\dot{\alpha}_1| \le \overline{\kappa}_1$ and $|\ddot{\alpha}_1| \le \overline{\kappa}_2$ for all $t \ge 0$, where κ_1, κ_2 are positive constants and $\varphi_1(0) = \alpha_1(0)$, $\varphi_2(0) = 0$, then for any $\mu > 0$, there exist $0 < \zeta \le 1$, $w_n > 0$, such that $|\varphi_1 - \alpha_1| \le \mu$, $|\dot{\varphi}_1$, $|\ddot{\varphi}_1$ and $|\dddot{\varphi}_1$ are bounded.

FINITE TIME COMMAND FILTERED ADAPTIVE FUZZY CONTROLLER DESIGN AND STABILITY ANALYSIS

Controller design

In this section, a finite time command filtered adaptive fuzzy backstepping design scheme is put forward to ensure the control target.

Layout the following coordinate transformation:

$$\begin{aligned} z_1 &= x_1 - y_r \\ z_2 &= x_2 - x_{2,c} \end{aligned} \tag{7}$$

where $z_i (i = 1,2)$ is the tracking error, y_r is reference signal and $x_{2,c}$ is the output of command filter with α_1 as input. The command filter is defined as

$$\begin{aligned} \dot{\varphi}_{1,1} &= w_2 \varphi_{1,2} \\ \dot{\varphi}_{1,2} &= -2\zeta w_2 \varphi_{1,2} - w_2(\varphi_{1,1} - \alpha_1) \end{aligned} \tag{8}$$

Where $x_{2,c} = \varphi_{1,1}$ as the output of filter and the filter input signal is α_1. The initial conditions are $\varphi_{1,1} = \alpha_1(0)$ and $\varphi_{1,2}(0) = 0$. For the error caused by the command filter, the following compensation signals are designed to eliminate the error.

$$\begin{aligned} \dot{\xi}_1 &= -c_1 \xi_1 + \xi_2 + x_{2,c} - \alpha_1 \\ \dot{\xi}_2 &= -c_2 \xi_2 \end{aligned} \tag{9}$$

According to reference [7,8], the compensating signals $\xi_i (i = 1,2)$ is bounded. Then, the compensated tracking error signals $v_i (i = 1,2)$ can be defined as

$$\begin{aligned} v_1 &= z_1 - \xi_1 \\ v_2 &= z_2 - \xi_2 \end{aligned} \tag{10}$$

Step 1: The derivative of v_1 is

$$\begin{aligned} \dot{v}_1 &= \dot{z}_1 - \dot{\xi}_1 \\ &= \dot{x}_1 - \dot{y}_r + c_1 \xi_1 - \xi_2 - x_{2,c} + \alpha_1 \\ &= v_2 - \dot{y}_r - c_1 v_1 + c_1 z_1 + \alpha_1 \end{aligned} \tag{11}$$

Consider establishing the following Lyapunov function

$$V_1 = \frac{1}{2} v_1^2 \tag{12}$$

Then time derivative of V_1 can gain

$$\begin{aligned} \dot{V}_1 &= v_1 \dot{v}_1 \\ &= v_1(v_2 - \dot{y}_r - c_1 v_1 + c_1 z_1 + \alpha_1) \\ &= -c_1 v_1^2 + v_1 v_2 + v_1(c_1 z_1 - \dot{y}_r + \alpha_1) \end{aligned} \tag{13}$$

Construct the virtual control α_1 as

$$\alpha_1 = -c_1 z_1 + \dot{y}_r - k_1 v_1^{2p-1} \tag{14}$$

where $k_1 > 0$ is a know constant.

Utilization of (14), yields

$$\dot{V}_1 = -c_1 v_1^2 + v_1 v_2 - k_1 v_1^{2p} \tag{15}$$

Step 2: By taking the derivative of v_2 is

$$\begin{aligned} \dot{v}_2 &= \dot{z}_2 - \dot{\xi}_2 \\ &= \dot{x}_2 - \dot{x}_{2,c} + c_2 \xi_2 \\ &= \tau u + f(x,\beta,u) - \dot{x}_{2,c} + c_2 \xi_2 \\ &= -c_2 v_2 + \tau u + f(x,\beta,u) - \dot{x}_{2,c} + c_2 z_2 \end{aligned} \tag{16}$$

Using the FLS to approximate the unknown part as

$$f(x,\beta,u) = \theta^T \phi + \varepsilon \tag{17}$$

Seeing that the Lyapunov function V_2 as follows

$$V_2 = V_1 + \frac{1}{2} v_2^2 + \frac{1}{2\gamma} \tilde{\theta}^2 \tag{18}$$

where $\gamma > 0$ is the design parameters, $\hat{\theta}$ is estimation of θ, and define error $\tilde{\theta} = \theta - \hat{\theta}$.

The time derivative of V_2 along the solutions of (16) and (17) is

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + v_2 \dot{v}_2 + \frac{1}{\gamma} \tilde{\theta} \dot{\tilde{\theta}} \\ &= \dot{V}_1 - c_2 v_2^2 + v_2(\tau u + c_2 z_2 - \dot{x}_{2,c} \\ &\quad + \theta^T \phi + \varepsilon) - \frac{1}{\gamma} \tilde{\theta} \dot{\hat{\theta}} \end{aligned} \tag{19}$$

Using Young's inequality

$$\begin{aligned} \nu_2\varepsilon &\le \frac{1}{2}\nu_2^{\,2} + \frac{1}{2}\varepsilon^2 \\ \nu_2\theta^T\phi &\le \frac{1}{\eta}\theta\phi^T\phi\nu_2^{\,2} + \frac{\eta}{4} \end{aligned} \tag{20}$$

where $\eta > 0$ is the design parameter.

Substituting (20) into (19), yields

$$\begin{aligned} \dot{V}_2 \le & -\sum_{i=1}^{2} c_i\nu_i^2 + \nu_1\nu_2 - k_1\nu_1^{2p} \\ & +\nu_2(\tau u + c_2 z_2 - \dot{x}_{2,c} + \frac{1}{2}\nu_2 \\ & +\frac{1}{\eta}\hat{\theta}\phi^T\phi\nu_2) + \tilde{\theta}(\frac{1}{\eta}\phi^T\phi\nu_2^{\,2} \\ & -\frac{1}{\gamma}\dot{\hat{\theta}}) + \frac{\eta}{4} + \frac{1}{2}\varepsilon^2 \end{aligned} \tag{21}$$

Choosing the controller u as

$$\begin{aligned} u = & \frac{1}{\tau}(-c_2 z_2 + \dot{x}_{2,c} - \nu_1 - \frac{1}{2}\nu_2 \\ & -\frac{1}{\eta}\hat{\theta}\phi^T\phi\nu_2 - k_2\nu_2^{2p-1}) \end{aligned} \tag{22}$$

where k_2>0 is a know constant.

Choosing the adaptive law $\hat{\theta}$ of

$$\dot{\hat{\theta}} = \frac{\gamma}{\eta}\phi^T\phi\nu_2^{\,2} - \Gamma\hat{\theta} \tag{23}$$

where $\Gamma > 0$ is the design parameter.

Invoking (22) and (23), (21) becomes

$$\begin{aligned} \dot{V}_2 \le & -\sum_{i=1}^{2} c_i\nu_i^2 - \sum_{i=1}^{2} k_i\nu_i^{2p} + \frac{\Gamma}{\gamma}\tilde{\theta}\hat{\theta} \\ & +\frac{\eta}{4} + \frac{1}{2}\varepsilon^2 \end{aligned} \tag{24}$$

Stability analysis

Theorem 1: For twin roll inclined casting system (1), on the understanding that Assumption 1, Lemma 1, Lemma 2, Lemma 3, we can choose the command filter (8), the error compensation signals (9), the virtual control (14) and the controller (22), the adaptive law (23), such that all signals in the closed-loop system are bounded.

Proof: It is not difficult to arrive at the following inequality

$$\frac{\Gamma}{\gamma}\tilde{\theta}\hat{\theta} \le -\frac{\Gamma}{2\gamma}\tilde{\theta}^2 + \frac{\Gamma}{2\gamma}\theta^2 \tag{25}$$

$$\Gamma(\frac{\tilde{\theta}}{2\gamma})^p \le \frac{\Gamma}{2\gamma}\tilde{\theta}^2 + \Gamma(1-p)p^{\frac{1-p}{p}} \tag{26}$$

Substituting (25) and (26) into (24), have

$$\begin{aligned} \dot{V}_2 & \le -\sum_{i=1}^{2} c_i\nu_i^2 - b\sum_{i=1}^{2} k_i(\nu_i^2)^p - b(\frac{\tilde{\theta}^2}{2\gamma})^p + c \\ & \le -aV_2 - bV_2^p + c \end{aligned} \tag{27}$$

where $a = \min\{2c_i, i=1,2\}, b = \min\{2^p k_i, \Gamma, i=1,2\}$, $c = \frac{\eta}{4} + \frac{1}{2}\varepsilon^2 + \frac{\Gamma}{2\gamma}\theta^2 + \Gamma(1-p)p^{\frac{1-p}{p}}$.

According to Lemma 1 and (27), Means that the trajectory of the closed loop system is bounded and stable in a finite time

$$\|\nu_i\| \le \sqrt{2(\frac{c}{(1-\lambda)b})^{\frac{1}{p}}} \tag{28}$$

Now that $z_i = \nu_i + \xi_i$ and ξ_i is bounded, z_i is bounded. This completes the proof.

SIMULATION STUDIES

In this section, simulation studies are used to illustrate the effectiveness of the proposed scheme. For twin roll inclined casting model, The system (1) parameters are chosen as R = 150 mm, L_r = 200 mm, ω = 10 mpm and β = 5. The reference signal is $y_r = \sin t$.

The system control parameters are designed as k_1 = 0,1, k_2 = 0,5, c_1 = 10, c_2 = 15, $\tau\zeta\eta\gamma\Gamma$ = 0,9, ζ = 0,4, w_2 = 40, γ = 0,1, η = 10, Γ = 0,5, p = 99/101.

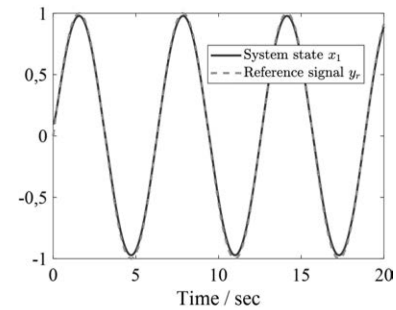

Figure 2 State trajectories of x_1 and y_r

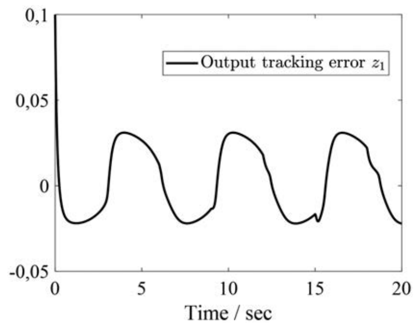

Figure 3 Tracking error trajectories of z_1

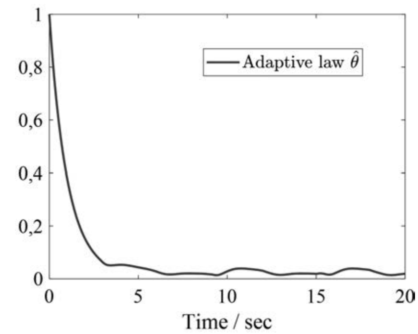

Figure 4 Adaptive parameter $\hat{\theta}$

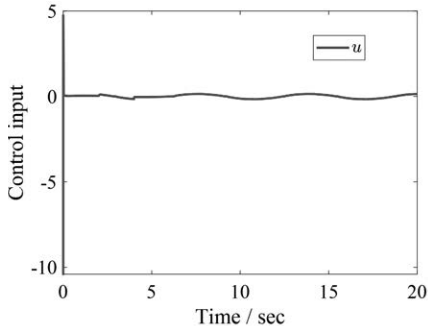

Figure 5 Control input *u*

The initial values are chosen as $x_1(0) = 0{,}2$, $x_2(0) = 0{,}2$, $\hat{\theta}(0) = 0{,}8$, $\xi_1(0) = \xi_2(0) = 0$.

The numerical simulation images are shown in Figures 2-5.

CONCLUSIONS

Focused on the twin roll inclined casting system, this paper come up with an adaptive fuzzy control scheme for finite time command filtering. Using the finite time stability as the judgment basis, it is proved that the tracking performance and the closed-loop system stability can be maintained in the finite time. In the end, simulation experiment shows that the proposed scheme is effective.

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