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ADAPTIVE FAULT ESTIMATION (FE) AND FAULT-TOLETANT CONTROL (FTC) FOR THE MOLTEN STEEL LEVEL IN A STRIP CASTING PROCESS

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In this paper, the problem of adaptive fault estimation and fault-tolerant control is studied for molten steel level for twin roll strip casting systems with the inclined angle and actuator fault. Firstly, an intermediate estimator and an adaptive state observer are designed to estimate actuator fault and unknown states respectively. Then, based on back-stepping method, a neural fault-tolerant controller and adaptive laws are constructed, which can ensure that the output signal of the systems can track the reference signal under inclined angle and actuator fault. Finally, the effectiveness of the studied control strategy is verified by semi-experimental systems dynamic model.

Keywords: strip casting process, molten steel level control, FE, FTC

INTRODUCTION

With the continuous development of industrial science and technology, the demand for thin strip steel is constantly expanding, so the production of thin strip steel has been widely concerned [1-2]. Two-roll inclined casting technology has a distinct advantage of saving energy, saving space and increasing casting speed [3]. Reference [4] studied the diverse production factors on the segregation behavior of alloying elements. In [5], an adaptive neural event-triggered control problem was studied for twin roll strip casting systems with inclined angle.

On the other hand, the double roll strip steel inclined continuous casting systems will inevitably occur fault in a long time operation, thus, it is necessary to consider the systems model with some faults. To reduce the periodic disturbances in casting strip steel, an iterative learning control algorithm with fault detection was designed in [6] for two-roll casting system. In work [7], an adaptive fault estimation (FE) and fault-tolerant control (FTC) problem was considered for a class of nonlinear systems with process fault. In work [8], an output feedback controller was designed for feedback nonlinear systems with unknown states, the radial basis function neural network (RBFNN) was used to approximate unknown dynamics.

Based on the above discuss, adaptive FE and FTC strategy is studied for twin roll strip casting systems with the inclined angle and actuator fault. By constructing an intermediate estimator, the actuator fault is compensated effectively. Furthermore, the designed adaptive state neural observer and FTC strategy can ensure that the systems output can track the reference signal and all closed-loop signals are bounded. Finally, simulation results show the effectiveness of the proposed strategy.

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SYSTEM MATHMATICAL MODEL OF THE STRIP CASTING PROCESS

In the process of double-roll inclined casting and rolling, when the molten pool works for a long time, it may lead to the increase of inclination angle and the change of molten steel velocity, so it is of great practical importance to study the problem of inclination angle and actuator fault. Figure 1 shows the double-roll inclined casting and rolling system with inclined angle and actuator fault.

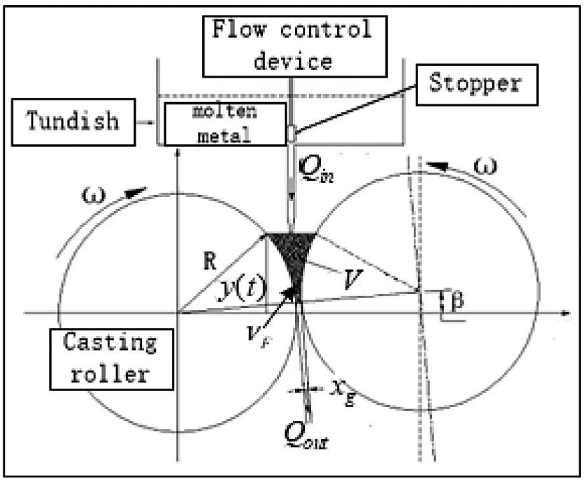

Figure 1 Schematic view of the twin-roll inclined casting systems with inclined angle and actuator fault

In the above schematic view, $x_g(t)$ is the gap between the rolls, $y(t)$ is the height of molten metal, R is the roll radius, V is the volume of the molten steel stored between the twin-roll cylinders, Q_{in} and Q_{out} are the input and output streams of the pool between the two roll, ω, β and v_F are the rotational velocity, inclined angle and actuator fault, respectively.

According to the previous work [5], by taking coordinate transformations $x_1 = y$ and $x_2 = dy/dt$, and further considering the case with actuator fault v_F, the systems model of liquid steel level in strip continuous casting process can be modeled as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \rho(u + v_F) + F(x_1, x_2, \dot{x}_2, \beta, u) \\ y &= x_1 \end{aligned} \tag{1}$$

where $F(x_1, x_2, \dot{x}_2, \beta, u) = \rho u + x_2 f_1(x_1, \beta) + f_2(x_1, \beta) + (g - \rho)u$, $g(\cdot) = \tau x_1 / L_r N$, $f_1(\cdot) = k x_1^2 \upsilon / N$, $f_2(\cdot) = N_0 / N$, $N = x_1 \cos\beta - (2R + kx_1)\cos\beta \sin\beta$, $N_0 = (2R + kx_1)\cos\beta - \sqrt{R^2 - x_1^2} - \sqrt{R^2 - (x_1 - (2R + kx_1)\sin\beta)^2}$. Besides, ρ is the known designed parameter, k, u, τ, υ, L_r are unknown parameter, the electric servomotor control input, the corresponding control gain, the roll surface tangential velocity and the length of the roll cylinders, respectively.

In this paper, the control purpose is to design FTC strategy such that the systems output can track the given reference signal in the presence of actuator fault and all closed- loop signals are bounded. To ensure the control purpose, we need to introduce the following assumptions and lemma.

Assumption 1 ([1]) The reference signals y_d and its derivative $\dot{y}_d$ are assumed known and bounded function.

Assumption 2 ([7]) The actuator fault v_F and its derivative $\dot{v}_F$ are also assumed known and bounded function, i.e., there are positive constant $\bar{v}_F$ such that $|\dot{v}_F| \le \bar{v}_F$.

Lemma 1 ([8]) For any unknown function $f(x)$, any $\varepsilon > 0$ and the compact set Ω_x, there exists RBFNN such that

$$f(x) = W^T S + \varepsilon(x), \quad |\varepsilon(x)| < \bar{\varepsilon} \tag{2}$$

where $x \in \Omega_x$, $\varepsilon(x)$ is approximate error, $\bar{\varepsilon}$ is the bound of $\varepsilon(x)$. $W = [W_1, \cdots, W_N]^T$ and $S = [S_1, \cdots, S_N]^T$ are the weight vector and basis function vector, respectively. Besides, the ideal weight vector is chose as

$$W^* = \arg\min_{W \in \Omega_W} \{\sup_{x \in \Omega_x} | f(x) - W^T S |\} \tag{3}$$

ADAPTIVE FAULT ESTIMATION NEURAL OBSERVER DESIGN

According to Lemma 1, the FE neural observer can be designed as

$$\begin{aligned} \dot{\hat{x}}_1 &= \hat{x}_2 + l_1(y - \hat{y}) \\ \dot{\hat{x}}_2 &= \rho(u + \hat{v}) + l_2(y - \hat{y}) + \hat{W}^T S \\ \hat{y} &= \hat{x}_1 \end{aligned} \tag{4}$$

with FE adaptive law

$$\dot{\hat{\eta}} = -\lambda(\rho u + \hat{W}^T S + \lambda\rho\hat{x}_2) - \lambda\rho\hat{\eta} \tag{5}$$

where $\hat{W}$, $\hat{v}$, $\hat{\eta}$ are the estimations of W, v, η, and η is the intermediate estimator designed in (11). l_1, l_2, $\lambda > 0$ are designed parameters.

Define error vector $e_i = x_i - \hat{x}_i$, $i = 1, 2$ and $\tilde{W} = W - \hat{W}$, $\tilde{\eta} = \eta - \hat{\eta}$, $\tilde{v} = v_F - \hat{v}$. According to (1), (4) and (5), error systems is written as:

$$\dot{e} = Ae + B(\tilde{W}^T S + \varepsilon + \rho\tilde{v}) \tag{6}$$

where $A = \begin{bmatrix} -l_1 & 1 \\ -l_2 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$, $e = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}$, we can choose l_1 and l_2 such that A is Hurwitz. For any matrix $Q = Q^T > 0$, there exists $P = P^T > 0$ such that $A^T P + PA = -Q$.

Lemma 2 Consider error systems (6), under Assumptions 1 and 2, the FE neural observer (4) and FE adaptive law (5) can ensure that error vector $\tilde{v}$ is bounded.

Proof: First introduce the error variable as

$$\eta = v_F - \lambda x_2 \tag{7}$$

so $\hat{\eta} = \hat{v} - \lambda\hat{x}_2$. Further, it can be obtained

$$\dot{\tilde{\eta}} = \dot{v}_F - \lambda(\tilde{W}^T S + \varepsilon + \rho\tilde{\eta} + \lambda\rho e_2) \tag{8}$$

Then, selecting the Lyapunov function as

$$V_0 = e^T P e + \frac{1}{2\lambda}\tilde{\eta}^2 \tag{9}$$

Taking the time derivative of V_0 with (5)-(8), one has

$$\begin{aligned} V_0 \le& -e^T Q e + 2e^T PB(\tilde{W}^T S + \varepsilon + \rho\tilde{v}) \\ &+ \frac{1}{\lambda}\tilde{\eta}\dot{v}_F - \tilde{\eta}(\tilde{W}^T S + \varepsilon + \rho\tilde{\eta} + \lambda\rho e_2) \end{aligned} \tag{10}$$

Then according to the triangle inequality and Assumption 2, it is easy to obtain

$$\begin{aligned} \dot{V}_0 \le& -e^T\left(Q - a_0 I\right)e - \gamma_0\tilde{\eta}^2 + \frac{3}{2}\tilde{W}^T\tilde{W} \\ &+ \frac{3}{2}\bar{\varepsilon}^2 + \frac{1}{2\lambda^2}\bar{v}_F^2 \end{aligned} \tag{11}$$

where $a_0 = 4\|P\|^2 + 3\lambda^2\rho^2/2$, $\gamma_0 = \rho - \rho^2 - 2$, $S^T S \le 1$. The proof is completed.

ADAPTIVE FAULT-TOLERANT CONTROLLER DESIGN

First of all, define the error variables $z_1 = x_1 - y_d$ and $z_2 = \hat{x}_2 - \kappa$, where κ is the virtual controller in (15). Then the Lyapunov function is designed as:

$$V_1 = \frac{1}{2}z_1^2 \tag{12}$$

The time derivative of V_1 can be obtained as

$$\dot{V}_1 = z_1(z_2 + \kappa + e_2 - \dot{y}_d) \tag{13}$$

Utilizing triangle inequality, we can get

$$z_1(e_2+z_2)\le z_1^2+\frac{1}{2}\|e\|^2+\frac{1}{2}z_2^2 \tag{14}$$

Designing virtual control as

$$\kappa=-c_1z_1-z_1+\dot{y}_d \tag{15}$$

where c_1 is a positive design parameter, then substituting (14) and (15) into (13) yields

$$\dot{V}_1\le -c_1z_1^2+\frac{1}{2}z_2^2+\frac{1}{2}\|e\|^2 \tag{16}$$

Next choose the Lyapunov function V_2 as:

$$V_2=V_1+\frac{1}{2}z_2^2+\frac{1}{2}\tilde{W}^T\Gamma^{-1}\tilde{W}+\frac{1}{2r}\tilde{\theta}^2 \tag{17}$$

where $\Gamma>0$, $r>0$ are design parameters, $\tilde{\theta}$ is estimation error with $\tilde{\theta}=\theta-\hat{\theta}$. Then, it has

$$\begin{aligned}\dot{V}_2&=\dot{V}_1+z_2(\rho(u+\hat{v})+l_2e_1+\hat{W}^TS-\dot{\kappa})\\&-r^{-1}\tilde{\theta}\dot{\hat{\theta}}-\tilde{W}^T\Gamma^{-1}\dot{\hat{W}}\\&\le \dot{V}_1+z_2(\rho(u+\hat{v})+\bar{F})-r^{-1}\tilde{\theta}\dot{\hat{\theta}}\\&-\tilde{W}^T(z_2S+\Gamma^{-1}\dot{\hat{W}})\end{aligned} \tag{15}$$

where $\bar{F}=l_2e_1+W^TS-\dot{\kappa}$. Based on Lemma 1, let $\theta=\|\vartheta\|^2$, we can get

$$\begin{aligned}z_2\bar{F}&=z_2(\vartheta^T\varphi+\Delta)\\&\le\frac{1}{2d^2}z_2^2\theta\varphi^T\varphi+\frac{1}{2}d^2+\frac{1}{2}z_2^2+\frac{1}{2}\bar{\Delta}^2\end{aligned} \tag{16}$$

where d is positive constant. Substituting (16) into (15) results in

$$\begin{aligned}\dot{V}_2&\le\dot{V}_1+z_2(\rho(u+\hat{v})+\frac{1}{2d^2}z_2\hat{\theta}\varphi^T\varphi)+r^{-1}\\&\tilde{\theta}(\frac{r}{2d^2}z_2^2\varphi^T\varphi-\dot{\hat{\theta}})-\tilde{W}^T(z_2S+\Gamma^{-1}\dot{\hat{W}})\\&+\frac{1}{2}d^2+\frac{1}{2}z_2^2+\frac{1}{2}\bar{\Delta}^2\end{aligned} \tag{17}$$

Thus, design the fault-tolerant controller and adaptive laws as

$$\begin{aligned}u&=\frac{1}{\rho}(-c_2z_2-z_2-\rho\hat{v}-\frac{1}{2d^2}z_2\hat{\theta}\varphi^T\varphi)\\\dot{\hat{\theta}}&=\frac{r}{2d^2}z_2^2\varphi^T\varphi-\delta_1\hat{\theta}\\\dot{\hat{W}}&=-\Gamma z_2S-\delta_2\hat{W}\end{aligned} \tag{18}$$

where c_2, δ_1, δ_2, Γ are positive design parameter. Combining (16), (17) and (18), we can get

$$\begin{aligned}\dot{V}_2&\le -c_1z_1^2-c_2z_2^2+\frac{\delta_1}{r}\tilde{\theta}\hat{\theta}+\delta_2\tilde{W}^T\hat{W}\\&+\frac{1}{2}\|e\|^2+\frac{1}{2}d^2+\frac{1}{2}\bar{\Delta}^2\end{aligned} \tag{19}$$

STABILITY ANALYSIS

Theorem 1 Considering systems model of liquid steel level in strip continuous casting process (1) satisfying Assumptions 1 and 2. The designed FE neural observer (4) and FTC strategy can guarantee that the tracking performance of the systems and all closed-loop signals are bounded.

Proof: Defining the final Lyapunov function $V=V_0+V_2$, according to (11) and (19), it has

$$\begin{aligned}\dot{V}&\le -e^T\left(Q-(a_0+\frac{1}{2})I\right)e-\gamma_0\tilde{\eta}^2-c_1z_1^2\\&-c_2z_2^2+\frac{\delta_1}{r}\tilde{\theta}\hat{\theta}+(\delta_2+\frac{3}{2})\tilde{W}^T\hat{W}\\&+\frac{1}{2}d^2+\frac{1}{2}\bar{\Delta}^2+\frac{3}{2}\bar{\varepsilon}^2+\frac{1}{2\lambda^2}\bar{\dot{v}}_F^2\end{aligned} \tag{20}$$

Note that

$$\begin{aligned}\tilde{\theta}\hat{\theta}&\le-\frac{1}{2}\tilde{\theta}+\frac{1}{2}\theta^2\\\tilde{W}^T\hat{W}&\le-\frac{1}{2}\|\tilde{W}^2\|+\frac{1}{2}\|\mathrm{W}\|^2\end{aligned} \tag{21}$$

Then, (20) becomes

$$\begin{aligned}\dot{V}&\le -e^T\left(Q-(a_0+\frac{1}{2})I\right)e-\gamma_0\tilde{\eta}^2-c_1z_1^2\\&-c_2z_2^2-\frac{\delta_1}{2r}\tilde{\theta}^2-(2\delta_2+3)\|\tilde{W}\|^2\\&+\frac{\delta_1}{2r}\theta^2+(2\delta_2+3)\|W\|^2\\&+\frac{1}{2}d^2+\frac{1}{2}\bar{\Delta}^2+\frac{3}{2}\bar{\varepsilon}^2+\frac{1}{2\lambda^2}\bar{\dot{v}}_F^2\\&\le-\pi_1V+\pi_2\end{aligned} \tag{22}$$

where $\pi_1=\min\{\frac{\lambda_{\min}(Q)-a_0-\frac{1}{2}}{\lambda_{\max}(P)}, 2\gamma_0\lambda, 2c_1, 2c_2, \delta_1, \frac{4\delta_2+6}{\lambda_{\max}(\Gamma)}\}$, $\pi_2=\frac{1}{2}(\frac{\delta_1}{r}\theta^2+(4\delta_2+6)\|W\|^2+c^2+\bar{\Delta}^2+3\bar{\varepsilon}^2+\frac{1}{\lambda^2}\bar{\dot{v}}_F^2)$.
Solving inequality (22) from 0 to t, one has $V(t)\le V(0)+\pi_1/\pi_2$. This means $V(t)$ is bounded, thus, all closed-loop signals of systems (1) are bounded. The proof is completed.

SIMULATION STUDIES

In this section, a semi-experimental systems dynamic model is given to illustrate the effectiveness of the studied method. Based on the model (1), the systems parameters are given as R = 150 mm, L_r = 200 mm, v = 10 mpm and β = 3°, the initial molten steel level is 70 mm. The reference signal and actuator fault are y = sin(t) and v_F = cos(t) According to Lemma 1, the NNs nodes is N = 5 from -2 to 2, width of the Gaussian functions is 1/2.

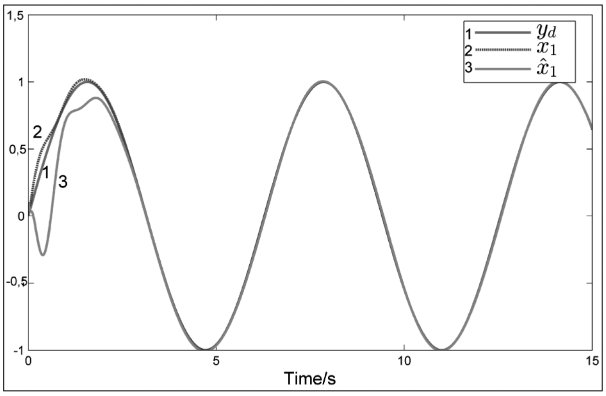

Figure 2 The response curves of y_d, x_1, $\hat{x}_1$

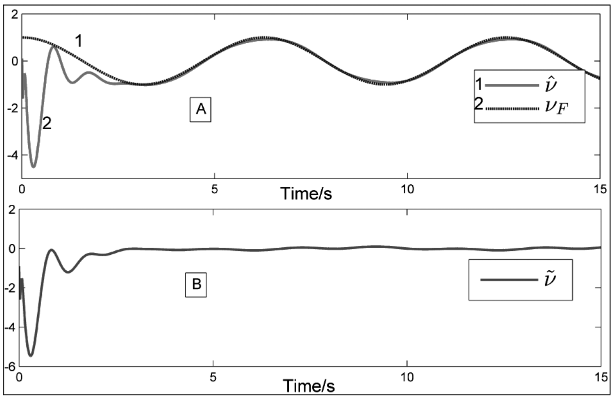

Figure 3 A: the response curves of $\hat{v}$, v_F; B: the response curves of $\tilde{v}$

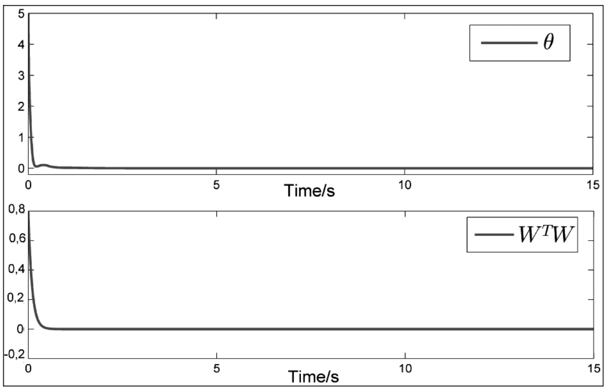

Figure 4 The response curves of θ, $W^T W$

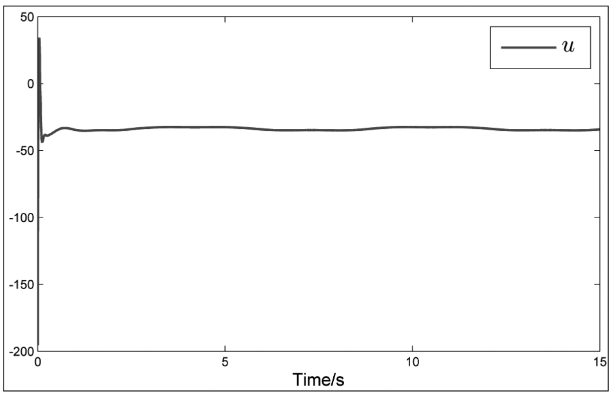

Figure 5 The response curves of u

In addition, the control parameters are designed as $c_1 = 40$, $c_2 = 60$, $l_1 = 5$, $l_2 = 50$, $\rho=\lambda=r=1$, $\delta_1=\delta_2=\Gamma=10$, $d = 8$; the initial values are chose as $x(0) = [0,1,0.1]^T$, $\hat{x}(0)=[0.1,0.1]^T$, $\hat{\eta}=0.1$, $\hat{W}_i(0) = 0.8$, $\hat{\theta}(0) = 5$. The simulation results are displayed in Figures. 2-5. Figure 2 shows the response curves of y_d, x_1, $\hat{x}_1$. The fault and its estimation are displayed in Figure 3. Figures 4 and 5 present the adaptive laws $\theta, W^T W$ and control signal u.

CONCLUSIONS

In this paper, an adaptive EF and FTC strategy is investigated for twin roll strip casting systems with the inclined angle and actuator fault. An adaptive state observer is constructed to estimate the unknown states, and an intermediate estimator is used to estimate the actuator fault. Then an adaptive FTC strategy is designed by using back- stepping method. The tracking performance is proved by Lyapunov stability analysis. Finally, the effectiveness of the proposed algorithm is verified by the simulation.

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