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.

**SYSTEM MATHEMATICAL 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.
In the above schematic view, \( x(t) \) 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, \( Q_i \) and \( Q_o \) are the input and output streams of the pool between the two roll, \( \omega \) and \( \beta \) 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 \( \nu_F \), the systems model of liquid steel level in strip continuous casting process can be modeled as

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= \rho(u + v_F) + F(x_1, x_2, \dot{x}_2, \beta, u) \\
y &= x_1
\end{align*}
\]

(1)

where

\[
F(x_1, x_2, \dot{x}_2, \beta, u) = \rho u + x_2 f_1(x_1, \beta) + f_2(x_1, \beta) + (g - \rho)u,
\]

\[
g(\tau) = x_1/L_N, \quad f_1(x_1, \beta) = \kappa \sqrt{\beta} x_2 / N,
\]

\[
f_2(x_1, \beta) = N_0 / N,
\]

\[
n_0 = x_1 \cos \beta (2R + x_1 \cos \beta \sin \beta), \quad \beta = -\sqrt{R^2 - x_1^2} - \sqrt{R^2 - (x_1 - 2R \cos \beta \sin \beta)^2}.
\]

Besides, \( \rho \) is the known designed parameter, \( k, u, \tau, v, L \) 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 \( \tilde{v}_F \) such that \( |v_F| \leq \tilde{v}_F \).

**Lemma 1 ([8])** For any unknown function \( f(x) \), any \( \epsilon > 0 \) and the compact set \( \Omega_x \), there exists RBFN such that

\[
f(\hat{x}) = W^T S + \varepsilon(x), \quad |\varepsilon(x)| \leq \tilde{\varepsilon}
\]

(2)

where \( x \in \Omega_x, \varepsilon(x) \) is approximate error, \( \tilde{\varepsilon} \) is the bound of \( \varepsilon(x) \). \( W = [W_1, \ldots, W_\kappa]^T \) and \( S = [S_1, \ldots, S_\kappa]^T \) are the weight vector and basis function vector, respectively. Besides, the ideal weight vector is chose as

\[
W^* = \arg\min_{w_{maj}} \{\sup_{x \in \Omega_x} |f(x) - W^T S|\}
\]

(3)

**ADAPTIVE FAULT ESTIMATION NEURAL OBSERVER DESIGN**

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

\[
\begin{align*}
\dot{\hat{x}}_1 &= \dot{\hat{x}}_2 + l_1(y - \hat{y}) \\
\dot{\hat{x}}_2 &= \rho(u + \hat{v}) + l_2(y - \hat{y}) + \hat{W}^T S \\
\dot{\hat{y}} &= \hat{x}_1
\end{align*}
\]

(4)

with FE adaptive law

\[
\begin{align*}
\dot{\eta} &= -\lambda (\rho u + \hat{W}^T S + \lambda \hat{x}_1) - \lambda \rho \hat{y} \\
\end{align*}
\]

(5)

where \( \hat{W}, \hat{v}, \hat{\eta} \) are the estimations of \( W, v, \eta \) and \( \eta \) 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 \( \hat{W} = W - \hat{W}, \hat{\eta} = \eta - \hat{\eta}, \hat{v} = v - \hat{v} \). According to (1), (4) and (5), error systems is written as:

\[
\dot{e} = Ae + B(\hat{W}^T S + \epsilon + \rho \hat{v})
\]

(6)

where

\[
A = \begin{bmatrix} -l_1 & 1 \\ -l_2 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad e = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}
\]

we can choose \( l_1 \) and \( l_2 \) such that \( A \) is Hurwitz. For any matrix \( Q > 0 \), 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 \( \hat{v} \) is bounded.

**Proof:** First introduce the error variable as

\[
\eta = v_F - \lambda x_1
\]

(7)

so \( \hat{\eta} = \hat{v} - \lambda \hat{x}_1 \). Further, it can be obtained

\[
\dot{\hat{\eta}} = \dot{\hat{v}} - \lambda(\dot{\hat{W}}^T S + \epsilon + \rho \dot{\hat{v}}) + \frac{1}{\lambda} \hat{\eta} v_F - \hat{\eta} \hat{W}^T S + \epsilon + \rho \hat{\eta} + \lambda \rho \hat{e}_2
\]

(8)

Then, selecting the Lyapunov function as

\[
V_0 = e^T P e + \frac{1}{2\lambda} \hat{\eta}^2
\]

(9)

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

\[
\dot{V}_0 \leq -e^T Q e + 2e^T PB(\hat{W}^T S + \epsilon + \rho \dot{\hat{v}}) + \frac{1}{\lambda} \hat{\eta} v_F - \hat{\eta} \hat{W}^T S + \epsilon + \rho \hat{\eta} + \lambda \rho \hat{e}_2
\]

(10)

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

\[
\dot{V}_0 \leq -e^T (Q - a_0 I) e - \gamma_0 \dot{\hat{\eta}}^2 + \frac{3}{2} \hat{\eta} \hat{W}^T \hat{W} + \frac{3}{2} \epsilon^2 + \frac{1}{2\lambda} \hat{\eta}^2 + \frac{1}{2\lambda} \hat{\eta}^2 + \frac{1}{\lambda} \hat{\eta}^2
\]

(11)

where

\[
a_0 = 4\|P\|^2 + 3\lambda^2 \rho^2 / 2, \quad \gamma_0 = \rho - \rho^2 - 2, \quad S^T S \leq 1.
\]

The proof is completed.

**ADAPTIVE FAULT-TOLERANT CONTROLLER DESIGN**

First of all, define the error variables \( z_i = x_i - y_d \) and \( z_i = \hat{x}_i - x_1 \), where \( k \) is the virtual controller in (15).

Then the Lyapunov function is designed as:

\[
V_1 = \frac{1}{2} z_i^2
\]

(12)

The time derivative of \( V_1 \) can be obtained as

\[
\dot{V}_1 = z_i (z_i + \kappa + e_2 - y_d)
\]

(13)
Utilizing triangle inequality, we can get
\[ z_i(z_i + z_j) \leq z_i^2 + \frac{1}{2} ||e||^2 + \frac{1}{2} z_j^2 \]  
(14)

Designing virtual control as
\[ \nu = -c_1 z_i + z_i + \dot{y}_d \]  
(15)

where \( c_1 \) is a positive design parameter, then substituting (14) and (15) into (13) yields
\[ \dot{V}_i \leq -c_1 z_i^2 + \frac{1}{2} z_i^2 + \frac{1}{2} ||e||^2 \]  
(16)

Next choose the Lyapunov function \( V_2 \) as:
\[ V_2 = V_i + \frac{1}{2} z_i^2 + \frac{1}{2} \dot{V}^T \Gamma^{-1} \dot{V} + \frac{1}{2 r} \dot{\theta}^2 \]  
(17)

where \( \Gamma > 0, r > 0 \) are design parameters, \( \dot{\theta} \) is estimation error with \( \dot{\theta} = \theta - \dot{\theta} \). Then, it has
\[ \dot{V}_2 = \dot{V}_i + z_i (\rho(u + \dot{v}) + \nu e + \dot{w} S - \kappa) - r^{-1} \dot{\theta} \dot{\theta} - \dot{w}^T \Gamma^{-1} \dot{w} \leq \dot{V}_i + z_i (\rho(u + \dot{v}) + \nu e - r^{-1} \dot{\theta}) - \dot{w}^T \Gamma^{-1} \dot{w} \]  
(15)

where \( \nu = \dot{e} + \dot{w}^T S - \kappa \). Based on Lemma 1, let \( \theta = ||\eta||^2 \), we can get
\[ z_i \dot{\nu} = z_i (\dot{\nu} \phi + \Delta) \leq \frac{1}{2} d z_i \dot{\theta} \phi \dot{\nu} + \frac{1}{2} d^2 z_i^2 \frac{1}{2} \Delta^2 \]  
(16)

where \( d \) is positive constant. Substituting (16) into (15) results in
\[ \dot{V}_2 \leq \dot{V}_i + z_i (\rho(u + \dot{v}) + \nu e - r^{-1} \dot{\theta}) - \dot{w}^T (z_i S + \Gamma^{-1} \dot{w}) \]  
(17)

Thus, design the fault-tolerant controller and adaptive laws as
\[ u = \frac{1}{\rho} (-c_2 z_i - \rho \dot{v} - \frac{1}{2d} z_i \dot{\theta} \phi \dot{\nu}) \]  
\[ \dot{\theta} = \frac{r}{2d} z_i \phi \dot{\nu} - \delta \dot{\theta} \]  
\[ \dot{w} = -\Gamma z_i S - \delta \dot{w} \]  
(18)

where \( c_2, \delta_1, \delta_2, \Gamma \) are positive design parameter. Combining (16), (17), and (18), we can get
\[ \dot{V}_2 \leq -c_2 z_i^2 - c_2 \frac{1}{r} \dot{\theta} \dot{\theta} + \delta \dot{w} + \delta \dot{w} \]  
(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 \( V = V_i + V_j \), according to (11) and (19), it has
\[ \dot{V} \leq -e^T (Q - (a_0 + \frac{1}{2} r) e - \gamma_0 \bar{y}^T - c_1 \bar{z}_i^2 - c_2 \frac{1}{r} \dot{\theta} \dot{\theta} + \delta \dot{w} + \delta \dot{w}) \]  
(20)

Note that
\[ \ddot{\theta} \leq -\frac{1}{2} \ddot{\theta} + \frac{1}{2} \dot{\theta} \]  
(21)

Then, (20) becomes
\[ \dot{V} \leq -e^T (Q - (a_0 + \frac{1}{2} r) e - \gamma_0 \bar{y}^T - c_1 \bar{z}_i^2 - \frac{1}{2} \Delta \dot{\theta} \dot{\theta} + \frac{1}{2} \Delta \dot{\theta} \dot{\theta}) \]  
(22)

Solving inequality (22) from 0 to \( t \), one has
\[ V(t) \leq V(0) + \pi_1 / \pi_2 \]  

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 \( R = 150 \text{ mm}, L_r = 200 \text{ mm}, v = 10 \text{ mpm} \) and \( \beta = 3^\circ \), the initial molten steel level is 70 mm. The reference signal and actuator fault are \( y = \sin(t) \) and \( v_e = \cos(t) \). According to Lemma 1, the NNs nodes is \( N = 5 \) from -2 to 2, width of the Gaussian functions is 1/2.
In addition, the control parameters are designed as \( c_1=40, c_2=60, l_1 = 5, l_2 = 50, \rho = \lambda = r = 1, \delta_1 = \delta_2 = l_1 = 10, \)
\( d = 8; \) the initial values are chose as \( x(0) = [0,1,0,1]^T, \)
\( \hat{x}(0)=[0,1,0,1]^T, \hat{y}(0)=0.1, \hat{W}(0) = 0.8, \hat{b}(0) = 5. \) 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 \( \theta, W^TW \) 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.

REFERENCES


Note: The responsible translators for English language is J. WANG-University of Science and Technology Liaoning, China