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Research Article

Active Fault Tolerant Control Based on a Novel Tracking Differentiator for Elevating Stage Control System

Haijie Mao ,[1,2] Wei Li ,[1,2] and Xiaolin Feng[1,2]

[1]*College of Electrical and Information Engineering, Lanzhou University of Technology, Lanzhou 730050, China*
[2]*Key Laboratory of Gansu Advanced Control for Industrial Process, Lanzhou 730050, China*

Correspondence should be addressed to Haijie Mao; gsmaohj@163.com

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In view of the speed sensor faults in elevating stage control system, an active fault tolerant control approach based on a novel tracking differentiator is proposed in this paper. First, the analytical redundancy relationship between the velocity and displacement signals in a dual closed loop control system is used to detect a fault. When the deviation between the differential of normal displacement sensor signal and the fault speed sensor output exceeds a certain threshold value, a fault can be considered to occur. Secondly, after a fault is detected, the output of the fault sensor is replaced immediately with the differential signal of the output from a normal sensor to ensure the safety of the postfault system. In the process of signal differential, considering the drawbacks of the traditional method which uses inertial element to approximate differentiator and complex parameter tuning of Han's Tracking Differentiator (TD), a novel tracking differentiator based on hyperbolic tangent function (Tanh-TD) is designed. Thirdly, in order to avoid the switching vibration and improve the reliability of FDD, a continuous smooth switching tactic based on exponential function is constructed. The simulation results show that the fault diagnosis method is simple and timely, the designed tracking differentiator is fast and effective, and the effect of the fault tolerant control based on smooth switching strategy is also satisfactory.

1. Introduction

As one kind of the most popular machinery in art performance, elevating stages have the function of delivering the actors and changing scenery as well as stage forms quickly to meet the needs of repertoire expression. The essential control variables of an elevating stage are position and speed. In order to realize a closed loop control with high precision, the photoelectric encoder is used to collect real-time position and velocity data. However, due to aging, disturbance, collision, and other factors, the encoder is prone to malfunction. Once the encoder fails, the fault influence will spread rapidly through the feedback loop, which will either produce substantial measurement errors or directly change the output properties, leading to system performance degradation and even jeopardizing the stability of the whole system, and resulting in loss of life and property. So the safety and reliability problems caused by encoder faults have attracted more and more attention in the stage machinery technology [1–3].

The fault tolerant control (FTC) theory has been used as one kind of new technique aiming to improve system reliability since 1980 and now has become an effective tool to tolerate the failures of the suspension system [4–8]. A control system that can accommodate the faults of system components automatically while maintaining system stability with a desired level of overall performance is denoted as a Fault Tolerant Control System (FTCS) [9]. Generally, there are two kinds of methods in FTC: Passive Fault Tolerant Control (PFTC) and Active Fault Tolerant Control (AFTC) [9–11]. In PFTC, component failures are assumed to be known a priori, and the control system takes all these failure modes into account in the design stage. As PFTC has to maintain the system stability under various component failures, the controller design has to be conservative. So it is very difficult for PFTC to be optimal from the performance point of view. In contrast, AFTC calculates fault information online with a Fault Detection and Diagnosis (FDD) block and redesigns a controller for the faulty system. It is able to deal with unforeseen faults and has the potential to achieve optimal performance for different system operating scenarios. Compared to PFTC, the AFTC method has a better overall performance and is more flexible in design, so it is used more widely [12–16]. In AFTC, the model-based method, the knowledge-based method, the data-based method, and other methods can be adopted [17–20]. The model-based method needs an accurate model for the system. It is a hard work, especially for a more complex system. The knowledge-based method needs more prior knowledge of faults and more experience from an operator. For lack of prior knowledge system, it has a limited scope of application. Considering that many kinds of faults will affect and change the features of process data, the data-based method has been widely used in recent years.

Several research papers on speed or position sensor FTC have been published. As to the position sensor faults in a Doubly Fed Induction Machine (DFIM), Abdellatif et al. [21] analyzed the fault effects on the direct torque control. In order to avoid system interruption, an AFTC technique based on angle tracking observer reconfiguration control is adopted. In [22], an effective fault detection and fault tolerant control strategy for an induction motor is proposed for the abrupt faults of speed sensor. The described approach can detect the encoder's healthy state and adjust the weight of the speed obtained from the encoder and that of the speed estimated based on MRAS. Akrad et al. [23] have made a AFTC study for position sensor faults. Based on the combination of one actual sensor and two virtual ones (one two-stage extended Kalman filter and one back electromotive-force adaptive observer), a voting algorithm parameterized with reliability coefficients is proposed for each sensor within a whole speed range so as to select an appropriate input of speed and position for the control loop.

Just as mentioned above, most of the researches for sensor fault AFTC are based on the observer method, which belongs to the model-based method. For the speed sensor faults in an elevating stage machinery control system, this paper proposes a novel AFTC method by referring to the idea of signal reconstruction, which is a kind of data-based method. First, with the analytical redundancy relationship between velocity and position in the dual closed loop system, through comparing the differential of normal displacement sensor with the output signal of speed sensor, a fault can be detected to occur when the residual exceeds a certain threshold. After the fault is detected, the output of the fault sensor is replaced immediately with the differential signal of the output from a normal displacement sensor to ensure the safety of the postfault system. In this process, how to design an effective differentiator is the key problem. Therefore, an effective differentiator based on hyperbolic tangent function is designed. Meanwhile, in the switching process, a continuous smooth switching tactic is implemented to reduce the switching transients and improve the reliability of FDD. The main contributions of the paper are (i) presenting an effective fault diagnosis and fault tolerant strategy for sensor faults; (ii) constructing a novel tracking differentiator based on hyperbolic tangent function; and (iii) designing a continuous smooth switching tactic based on exponential function.

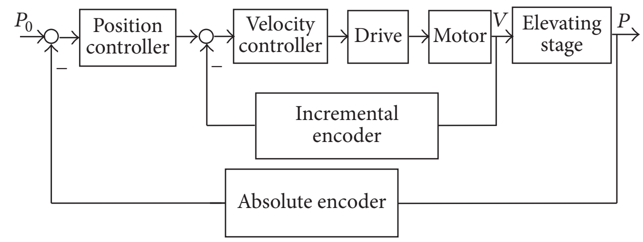


Figure 1: Block diagram of the elevating stage control system.

2. Structure of the Elevating Stage Control System

As a high frequency application device in a theater, elevating stage undertakes the important scenery task to transport stage props and staff. Due to its large size, it is commonly driven by two or more motors. In order to achieve the precise location, speed, and even the synchronization control between different motors, the system contains position and speed sensors to form a dual-loop feedback structure. Two signals which are measured by an incremental encoder and an absolute encoder, respectively, are used to feed back to a Variable-Frequency Drive or PLC and then compare with an expected value. Under the guidance of controllers, the system achieves its required control target. Figure 1 is the block diagram of an elevating stage control system for one motor.

In this system, due to the external disturbance, improper installation, or other uncertainties, the encoder which is usually installed on the motor spindle is prone to precision decrease and even to failure. When a sensor fault occurs in a double closed loop structure, the fault influence will spread rapidly through the feedback loop. As a result, the overall control system for the elevating stage will be further affected. So if the fault can be diagnosed quickly and compensated effectively, the control precision and reliability of the overall system will be guaranteed.

Considering the sensor failure, using the redundant information to realize compensation is the basic idea of AFTC based on signal or information reconstruction. In the block diagram of the elevating stage control system, velocity and displacement variables have an analytical redundancy relationship with each other. Here, it is assumed that only one of the two sensors fails at one point. Taking an incremental encoder fault as an example, a feasible way to compensate is to replace the fault signal with the differential of the displacement signal. It is similar to an absolute encoder fault. The integral of speed signal can be used to substitute the fault position signal. It means that the deviation between the reconstructed signal, that is the differential or integral signal of the output from the nonfaulty sensor, and the signal from the faulty sensor can be used to detect whether a failure happens or not. Once a fault is detected, the reconstructed signal will be utilized to substitute the fault signal to realize an active fault tolerant control. And that is the basic idea of this paper.

It should be pointed out that, according to the practical experience in engineering, the probability of the incremental encoder failure is higher, and the differentiator design for an incremental encoder fault is more complex than that for an integrator. So this paper mainly deals with the incremental encoder faults. Then how to design an effective differentiator? What strategy can be used to diagnose the faults and how to realize the switching? These are the critical problems. The next section will discuss the detailed researches for these problems.

3. Tracking Differentiator Design Based on Hyperbolic Tangent Function

The differentiator design is the key problem to obtain the differential of the displacement output and realize the reconstruction for the fault speed sensor. As an ideal differentiator is physically unachievable, the inertial element $1/(1 + Ts)$ is usually adopted to approximate it. Where the inertial time constant T is smaller, and the approximate precision is higher. However, the noise effect is amplified more seriously at the same time and it can even submerge the really useful differential signal. A Nonlinear Tracking Differentiator (NTD) is proposed by Han [24–26]. NTD can not only obtain a satisfactory differential signal, but also track the original signal properly even in the presence of noise. This method has its strong theory support in mathematics and good feasibility in engineering. So NTD has attracted much more attention [27–30] since it came into being. In construction of TD, the selection of comprehensive control function is the key problem. There are many literatures investigating different control functions to improve tracking and differential effects from the aspects of rapidity and accuracy [31–33]. In these methods, there exist more or less some drawbacks, such as complex functional form, tedious parameter setting, and output chattering. Through investigating the relationship between various forms of the comprehensive control function and the performance of TD, it is not difficult to draw the principles of selecting the comprehensive control function. First, in order to reduce the chattering caused by controller switching to ensure the rapidity of simultaneous tracking, the control function should have the characteristics of linear function when it is close to the equilibrium point and should have the nonlinear characteristics when it is far from the equilibrium point. Secondly, the function form should be smooth and continuous, and the parameter setting should be as simple and feasible as possible. Based on these principles, the paper uses the hyperbolic tangent function to design the tracking differentiator.

The following lemma needs to be given and proved for designing the tracking differentiator based on the hyperbolic tangent function.

Lemma 1. *Consider the following system Σ_1:*

$$\begin{aligned}\dot{z}_1(t) &= z_2(t),\\ \dot{z}_2(t) &= u(z_1(t), z_2(t)),\end{aligned} \tag{1}$$

where $u(\cdot)$ is a comprehensive control function and $z_1(t)$ and $z_2(t)$ are the states of system Σ_1.

We design

$$\begin{aligned}u(z_1(t), z_2(t)) = &-a_1 \tanh(b_1 z_1(t))\\ &- a_2 \tanh(b_2 z_2(t)),\end{aligned} \tag{2}$$

where $a_1, a_2, b_1, b_2 > 0$ are the tracking and filtering parameters, respectively, and $\tanh(\cdot)$ *is the hyperbolic tangent function. Then the system Σ_1 is asymptotically stable at the equilibrium point* $(0, 0)$ *and can meet the following conditions:*

$$\begin{aligned}\lim_{t\to\infty} z_1(t) &= 0,\\ \lim_{t\to\infty} z_2(t) &= 0.\end{aligned} \tag{3}$$

Proof. Consider the Lyapunov function candidate:

$$V(z_1, z_2) = \int_0^{z_1} a_1 \tanh(b_1 x)\, dx + \frac{1}{2} z_2^2. \tag{4}$$

For $a_1 > 0$, $b_1 > 0$, and when $z_1(t) > 0$, $x \in (0, z_1]$, then we have $a_1 \tanh(b_1 x) > 0$. If $z_1(t) < 0$, $x \in [z_1, 0)$, then $a_1 \tanh(b_1 x) < 0$, so according to the integral mean value theorem, we have

$$\int_0^{z_1} a_1 \tanh(b_1 x)\, dx = a_1 \tanh(b_1 \xi) \cdot z_1 > 0, \tag{5}$$

where ξ is between 0 and z_1.

So we have $\int_0^{z_1} a_1 \tanh(b_1 x) dx > 0$.

And similarly when $z_2 \neq 0$, $(1/2) z_2^2 > 0$, so $V(z_1, z_2) > 0$.

Taking the time derivative of $V(z_1, z_2)$, we have

$$\begin{aligned}\dot{V}(z_1, z_2) &= a_1 \tanh(b_1 z_1)\dot{z}_1 + z_2 \cdot \dot{z}_2\\ &= z_2 a_1 \tanh(b_1 z_1)\\ &\quad + z_2(-a_1 \tanh(b_1 z_1) - a_2 \tanh(b_2 z_2))\\ &= -a_2 z_2 \tanh(b_2 z_2).\end{aligned} \tag{6}$$

Correspondingly, for $a_2 > 0$, $b_2 > 0$, $a_2 z_2 \tanh(b_2 z_2) \geq 0$. If and only if $z_2 = 0$, $\dot{V}(z_1, z_2) = 0$.

According to the Lyapunov theory, the system Σ_1 will be asymptotically stable at the equilibrium point. □

Theorem 2. *Consider the following system Σ:*

$$\begin{aligned}\dot{x}_1(t) &= x_2(t),\\ \dot{x}_2(t) &= -R^2 [a_1 \tanh(b_1 (x_1(t) - v(t)))]\\ &\quad - R^2 \left[a_2 \tanh\left(b_2 \frac{x_2(t)}{R}\right)\right],\end{aligned} \tag{7}$$

where $v(t)$ is the input signal, $[x_1, x_2] \in R^2$ is the state vector, R is a real constant gain ($R > 0$), and parameters a_1, a_2, b_1, b_2 are positive. For any bounded input $v(t)$, the solution of system Σ can meet the condition

$$\lim_{R\to\infty} \int_0^T |x_1(t) - v(t)|\, dt = 0, \tag{8}$$

where T is a constant gain ($T > 0$). Then the system Σ is a tracking differentiator based on the hyperbolic tangent function (Tanh-TD).

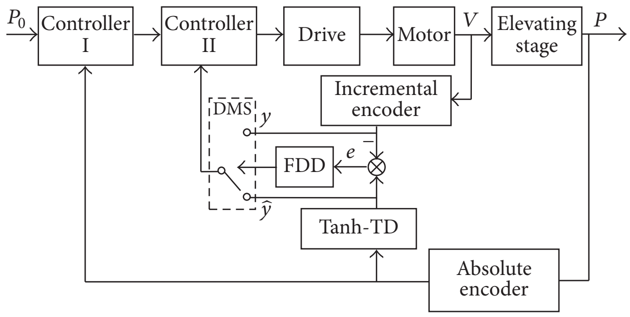


Figure 2: Block diagram of the active fault tolerant control.

The related proof is given in the Appendix.

The theorem illustrates that the solution of Σ can fully be close to the input signal $v(t)$ in any limited time T when R is large enough, and the differential of the input signal $x_2(t)$ can be effectively obtained.

4. Active Fault Tolerant Control for Speed Sensor Faults

4.1. Active Fault Tolerant Control Scheme. The block diagram of the active fault tolerant control for speed sensor faults is shown in Figure 2, where y is the actual output of the incremental encoder and $\hat{y}$ is the constructed signal processed by Tanh-TD. The system includes three key modules: (i) signal reconstruction module based on Tanh-TD; (ii) Fault Detection and Diagnosis (FDD) module, and (iii) Decision-Making and Switching (DMS) module. The working process of the AFTC scheme can be described as follows.

Step 1 (FDD). The residual signal is generated through comparing the differential of the displacement signal processed by Tanh-TD with the speed signal collected by the incremental encoder. When the residual exceeds a certain threshold, a fault can be determined to occur, and the fault indicator quantity changes from 0 to 1.

Step 2 (DMS). Once a fault is detected, the fault information provided by FDD will be given to DMS module, which executes the fault tolerant actions according to the predefined trigger logic. It will replace and isolate the fault sensor output signal with the differential of the displacement signal to realize the fault tolerant control.

In this process, the rapidity and reliability of FDD are very important. It is the foundation of the follow-up to achieve fault tolerance. Among various influencing factors of FDD's reliability, the residual decision is the most critical one. If the residual decision is inappropriate, a missing or false alarm will occur, which directly affects the effect of fault diagnosis and the implementation of the fault tolerant control.

Meanwhile, the effects of DMS depend on the type of Controller-II to some extent. As a feedback signal of the inner-loop, the output of DMS has a negative influence on the control performance because of the switching vibration. Therefore it is necessary to choose a robust and effective controller to avoid such drawback. However, in the actual elevating stage control engineering, the most widely used controller is PID which is usually embedded in a PLC or Variable-Frequency Drive. Our goal is to keep the existing hardware conditions unchanged. So how to avoid the adverse effects of switching vibration based on the existing hardware conditions is another problem needed to be solved in this paper.

4.2. Residual Decision for the Incremental Encoder Fault Diagnosis. Due to the existence of measurement noise and system noise in the actual system, the fault-free residual may not be equal to zero, and a fault residual is not a constant, and it may deviate from the normal range. So it is necessary to introduce an effective residual decision method. Considering the single sample set method has a low reliability, and the sliding data window method will generate a long time delay due to too many samples, this paper adopts the Sequential Probability Ratio Test (SPRT) method. This method does not need to determine the number of observation groups in advance but increases the amount of data in the process of inspection until a predetermined missing alarm and false alarm rate requires to stop the inspection. The algorithm is shown as follows.

First, a residual signal is generated

$$e(k) = \hat{y}(k) - y(k). \tag{9}$$

The observed random residue variables $e = [e_1, e_2, \dots, e_m]$ are assumed to obey the normal distribution $N_m(\theta, \delta)$.

Consider the following hypothesis test models:

H_0: $e_i \in N(0, \delta)$, $i = 1, 2, \dots, m$, fault-free

H_1: $e_i \in N(\theta_1, \delta)$, $i = 1, 2, \dots, m$, $\theta_1 \neq 0$, fault

The probability distribution density functions are, respectively,

$$P(e_i \mid H_0) = \frac{1}{\sqrt{2\pi}\delta} \exp\left(-\frac{e_i^2}{2\delta^2}\right), \tag{10}$$

$$P(e_i \mid H_1) = \frac{1}{\sqrt{2\pi}\delta} \exp\left(-\frac{(e_i - \theta_1)^2}{2\delta^2}\right). \tag{11}$$

As the observed variable e_i is independent from each other, we can define the likelihood ratio as follows:

$$\begin{aligned} L(m) &= \frac{P(e \mid H_1)}{P(e \mid H_0)} = \prod_{i=1}^{m} \frac{P(e_i \mid H_1)}{P(e_i \mid H_0)} \\ &= \exp\left(\sum_{i=1}^{m} \frac{2\theta_1 e_i - \theta_1^2}{2\delta^2}\right). \end{aligned} \tag{12}$$

Then we have the following: if $L(m) = P(e \mid H_1)/P(e \mid H_0) > 1$, H_1 is true; otherwise, H_0 is true.

Correspondingly, the log-likelihood ratio of (12) is

$$\begin{aligned} \lambda(m) &= \ln(L(m)) = \sum_{i=1}^{m} \frac{2\theta_1 e_i - \theta_1^2}{2\delta^2} \\ &= \sum_{i=1}^{m} \frac{\theta_1 e_i}{\delta^2} - \sum_{i=1}^{m} \frac{\theta_1^2}{2\delta^2} = \lambda(m-1) + \frac{2\theta_1 e_m - \theta_1^2}{2\delta^2}. \end{aligned} \tag{13}$$

SPRT uses the probabilities of missing alarms and false alarms to create the thresholds of acceptance and rejection of the null hypothesis. The false alarm probability P_F is defined as the probability that H_0 is rejected even though it is true. The missing alarm rate P_M is defined as the probability that H_0 is accepted when it is actually false. Then the thresholds are

$$T(H_0) = \frac{P_M}{1-P_F}, \quad T(H_1) = \frac{1-P_M}{P_F}. \tag{14}$$

A fault is detected based on the following rules:

$\lambda(m) \leq \ln T(H_0)$, H_0 is accepted, and system is normal.

$\lambda(m) \geq \ln T(H_1)$, H_1 is accepted, and system is under fault.

When $\ln T(H_0) \leq \lambda(m) \leq \ln T(H_1)$, the information is not sufficient to make a decision, and sampling continues.

In view of the plus or minus uncertainty of $\lambda(m)$ in the recursive process, the detection time delay will be created when $\lambda(m)$ is near to zero. As the effectiveness of real-time detection will decrease, an improvement is made as follows:

$$\lambda^*(m) = \begin{cases} \lambda(m), & \lambda(m) > 0, \\ 0, & \lambda(m) \leq 0. \end{cases} \tag{15}$$

4.3. A Reliable and Smooth Decision-Making Switching Design Based on Continuous Exponential Function. After a fault is detected, it is necessary to take immediate measures by switching the differential of the displacement signal of the encoder to ensure the stable operation of the system. This is just the fault tolerant control design. From the strategy analysis of fault detection mentioned above, we can see that it has two problems in this process. First, the vibration will occur when the system is switching from the fault signal y to the reconstruction signal $\hat{y}$. It will directly affect the AFTC performance. Although a robust controller can be adopted as mentioned in Section 4.1, other measures should be considered when the controller structure is difficult to change. Secondly, the uncertainty of FDD exists when the residual signal $\lambda(m)$ falls in the scope $(\ln(TH_0), \ln(TH_1))$. Generally it is believed no fault happens. However, a small or medium fault may have happened. That means the reliability of FDD is very low in this range. While the FTC strategy is only triggered when a fault is indicated with a high reliability, that means when $\lambda(m)$ exists in $(\ln(TH_0), \ln(TH_1))$, the system is in an unsafe condition. So in order to reduce the switching vibration transient and improve the reliability of FDD, the paper designs a continuous exponential function to realize a smooth and flexible switching. The specific design process is introduced as follows.

First, we construct an exponential function:

$$\alpha = \frac{1}{1 + \exp(-l(\lambda - \ln T(H_1)))}, \tag{16}$$

where α is defined as the reliability factor. $\ln T(H_1)$ is the larger threshold, and l is the approximate slope. When $\lambda > \ln T(H_1)$, $\alpha \approx 1$, and when $\lambda < \ln T(H_1)$, $\alpha \approx 0$. So $\alpha \in (0, 1)$.

Then, we design a function of λ which is related to α as follows:

$$f(\lambda) = \alpha\hat{y} + (1-\alpha) y. \tag{17}$$

From (17) and the fault diagnosis strategy mentioned above, we know the following:

(i) $f(\lambda)$ is a mixed signal combined with an actual output y and a reconstruction output $\hat{y}$.

(ii) When $\lambda(m) \leq \ln T(H_0) \leq \ln T(H_1)$, which is fault-free, $\alpha \approx 0$, so $f(\lambda) \approx y$; now the output is the actual signal from the incremental encoder.

(iii) When $\lambda(m) > \ln T(H_1)$, which is fault, $\alpha \approx 1$, $f(\lambda) \approx \hat{y}$; now the output is a reconstruction signal from the differential of the displacement signal of the fault-free absolute encoder.

(iv) When $\ln T(H_0) \leq \lambda(m) \leq \ln T(H_1)$, the output is the mixture of y and $\hat{y}$. Particularly in this range, as $0 < \alpha < 0.5$, it shows that the actual output accounts for a relatively large proportion. That is, when the fault diagnosis result is uncertain, the system should use the actual output as far as possible. It also accords with the actual logical strategy.

So through the above analysis, (17) can be specifically expressed as follows:

$$f(\lambda) = \begin{cases} \hat{y}, & \lambda > \ln(T(H_1)), \ \alpha \approx 1, \\ \alpha\hat{y} + (1-\alpha) y, & \ln(T(H_0)) < \lambda < \ln(T(H_1)), \\ y, & \lambda < \ln(T(H_0)), \ \alpha \approx 0. \end{cases} \tag{18}$$

Now, the DMS module in Figure 2 can be substituted by function $f(\lambda)$. It realizes a mixed continuous output of the reconstructed signal and the actual signal at different proportions based on the size of fault diagnosis reliability. Comparing to the direct switching in DMS, the vibration will not exist in $f(\lambda)$ smooth switching. Moreover, the high performance requirements for Controller-II can be reduced. Furthermore, the design of the smooth function improved the reliability of FDD relatively and realized the integrated design for the reliability of FDD and FTC.

4.4. Steps of Active Fault Tolerant Control. According to the above analysis, we can get the implementation steps of AFTC based on signal reconstruction.

Step 1. Specify the false alarm rate P_F and the missing alarm rate P_M and compute the threshold values $T(H_0)$ and $T(H_1)$.

Step 2. Comparing the actual output of the incremental encoder y with the reconstruction signal $\hat{y}$, we can obtain the residual signal $e(k)$ from formula (9) and acquire $\lambda(m)$ from formula (13).

Step 3. Implement the fault diagnosis and fault tolerant control based on the different size of $\lambda(m)$ with the aid of formula (17); especially when $\ln T(H_0) \leq \lambda(m) \leq \ln T(H_1)$, the fault indicator output is α, which is a number between 0 and 1. The system will continue to increase the sample data for inspection. And at the same time, the feedback signal of inner-loop is the mixture of y and $\hat{y}$.

5. Numerical Simulations and Results Analysis

5.1. Simulation Modeling. In view of the vector control for AC motor in stage machine engineering, the model for the AC motor can be approximately equivalent to that for the DC motor with vector transformation [34]. So under the rated excitation condition, the mathematic model can be expressed as follows:

$$G(s) = \frac{1/C_e}{T_m T_l s^2 + T_m s + 1}, \qquad (19)$$

where the torque coefficient C_e is 0.1925 V·min/r, the electromechanical time constant T_m is 0.075 s, and the electromagnetic time constant T_l is 0.017 s. Two conventional PI controllers are adopted, respectively, in the inner and outer control loop.

5.2. Tanh-TD Effective Verification. In order to verify the effectiveness of Tanh-TD, the tuning of parameters R, a_1, a_2, b_1, b_2 is the key point. Considering that the differential and the tracking roles are the same in the operation process of the comprehensive control function, we can set $a_1 = a_2 = a$ and $b_1 = b_2 = b$, so the number of the tuning parameters is reduced to 3, that is R, a, and b. Although the reduction of adjustable parameter number will reduce the freedom degree of Tanh-TD parameter optimization to some extent, it makes the choice of parameters more convenient. Thus, by analyzing the meanings of parameters and doing a large number of related experimental tests, we give the tuning guidelines as follows:

(i) Parameter a: as the amplitude of the comprehensive control function, the larger the value is, the larger the control energy is, and the faster the tracking speed is. But when it increases to a certain value, the rapidity of tracking slows down. At the same time, from the perspective of limited energy, the value should not be too large. So the recommended value interval is $[1, 20]$.

(ii) Parameter b: as the slope of the approximate linear interval of the comprehensive control function, the smaller the value is, the more smooth and wider the linear range is, and the faster the tracking speed is, but an overshoot will occur. So the choice must be balanced between the tracking speed and the stationarity. The proposed interval is $[0.1, 10]$.

(iii) Parameter R: as a system time scale, the larger the value is, the faster the tracking speed is. In view of its amplification effect on noise, it should not be too large. According to the tracking and filtering performance requirements, the proposed value interval is $[1, 50]$.

Now, the two different types of TD algorithm, DTD [35] which is the classical discrete TD and MTD [32] which is a new modified nonlinear-linear tracking differentiator, are chosen to compare with Tanh-TD by using unit-step and sine signal with noise as the input in Matlab/Simulink environment. The noise signal is white with mean to 0 and variance to 0.001. The parameters of three types of TD are showed in Table 1. It needs to be pointed out that the parameters of the three methods are all optimal. The simulation results are showed in Figures 3 and 4.

Table 1: Parameter setting.

TD	Parameters
DTD	$R = 30,\ h0 = 0.01,\ h = 0.001$
MTD	$R = 30,\ a = b = 5,\ m = 3$
Tanh-TD	$R = 30,\ a1 = a2 = 10,\ b1 = b2 = 1$

Table 2: The filtering effect.

TD	SNR
DTD	11.4379
MTD	17.2052
Tanh-TD	17.8132

Table 3: Types of sensor faults.

Fault type	Mathematic expression
Constant gain	$\tilde{y}(k) = y(k) + c_1$
Locked	$\tilde{y}(k) = c_2$
Constant deviation	$\tilde{y}(k) = c_3 y(k)$

Figure 3(a) shows the step signals with noise and the tracking results of DTD, MTD, and Tanh-TD. Figure 3(b) displays the comparison of differential signals obtained from the three types of TD. As shown in Figure 3, Tanh-TD has a fast tracking and better differential effect than DTD and MTD. As showed in Figure 4, the differential effect for sine signal is also satisfactory. The filtering effect of the three types of TD for sine signal is given in Table 2. The Signal to Noise Ratio (SNR) of Tanh-TD is obviously higher than those of the other two methods.

5.3. Encoder Fault Type Description. In order to simulate the faults of the incremental encoder, we should analyze the fault causes and fault types in practical engineering first. Generally speaking, as the faults of a general sensor, there are three types of faults in the encoder [36]:

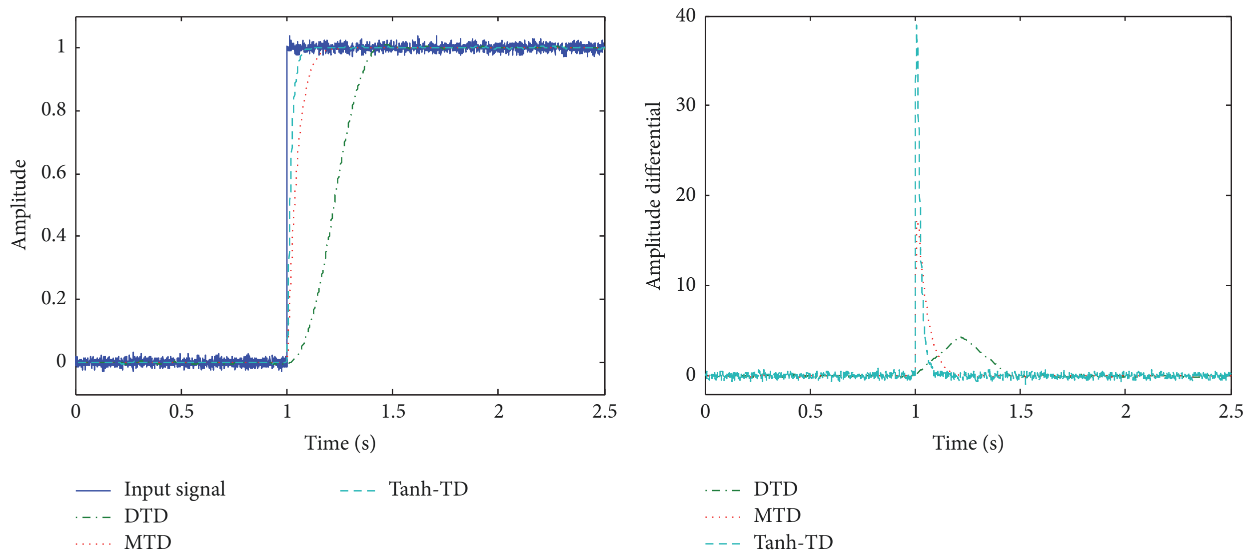
(i) Constant gain fault: it may be caused by circuit parameter drift or precision decline.

(ii) Locked fault: it may be caused by hardware damage.

(iii) Constant deviation fault: it may be caused by code or information losing.

The fault types and their corresponding mathematics descriptions are showed in Table 3.

5.4. Simulation Results and Analysis. In order to verify the proposed fault diagnosis and fault tolerant control strategy, we carry out the related simulations under different scenarios. The simulation parameters are designed as follows: the motor speed is set to 100 rpm, and the position is 2000 m. The



(a) The tracking result

(b) The differential result

Figure 3: Comparison of different TDs for step signal inputs.

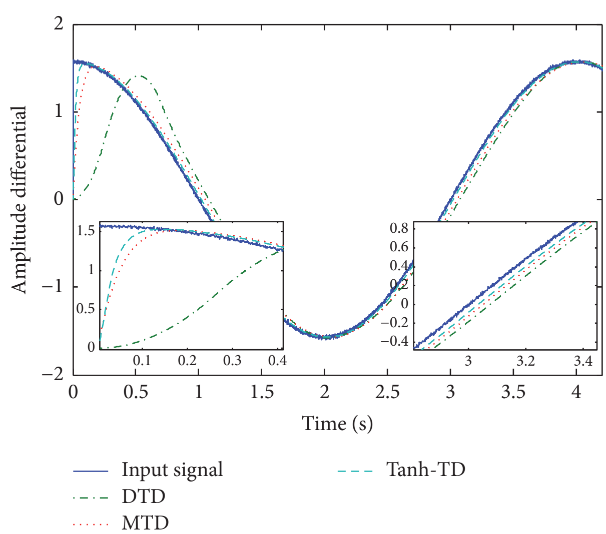


Figure 4: Differential results comparison of different TDs for sine signal inputs.

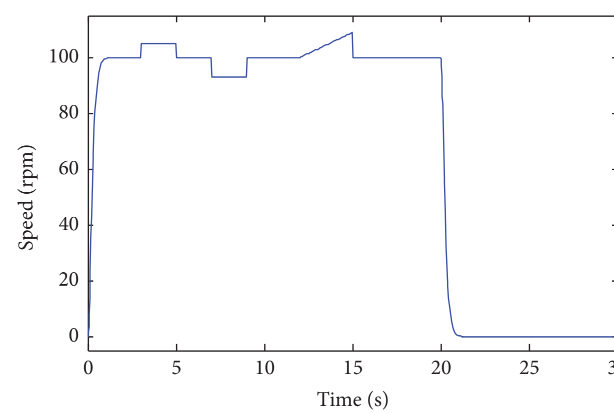


Figure 5: Fault speed sensor (incremental encoder) output.

different types of faults, constant gain fault ($c_1 = 5$), locked fault ($c_2 = 93$), and constant deviation fault ($c_3 = 3$) occur at 3~5 s, 7~9 s, and 12~15 s, respectively. The fault diagnosis and fault tolerant control strategy specified in Section 4.4 is employed, where $P_F = 0.01$, $P_M = 0.01$, and $\theta_0 = 0.0885$.

The simulation results are showed from Figures 5–9.

Figure 5 shows the speed sensor output with faults. Figure 6 displays the residual and fault indicator. From Figures 5 and 6, it can be seen that when different types of faults occur at 3 s and 7 s, the residue increases sharply, which causes the fault indicator to change from 0 to 1. That means the faults are detected immediately. And when the

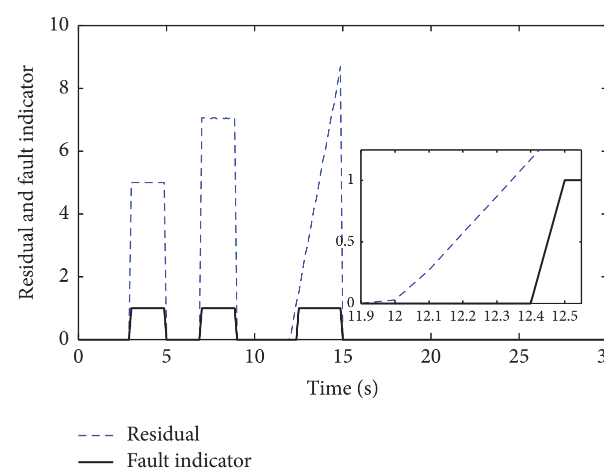


Figure 6: Residual and fault indicator.

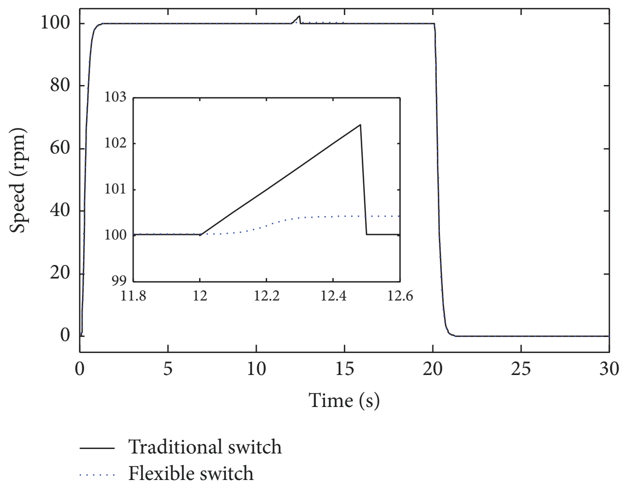


FIGURE 7: Speed output with traditional and flexible switching.

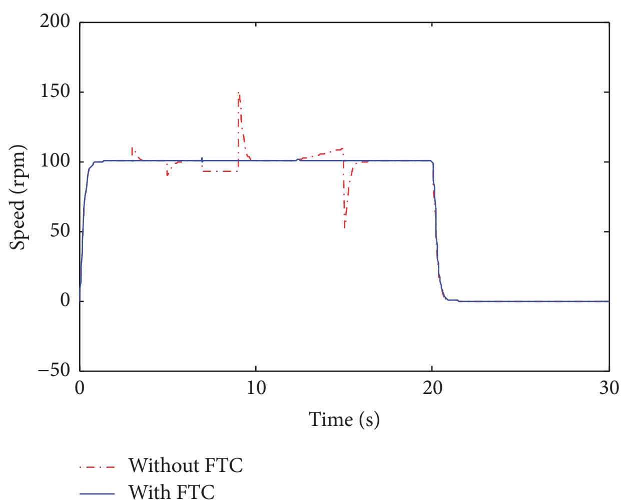


FIGURE 8: Speed output with and without FTC.

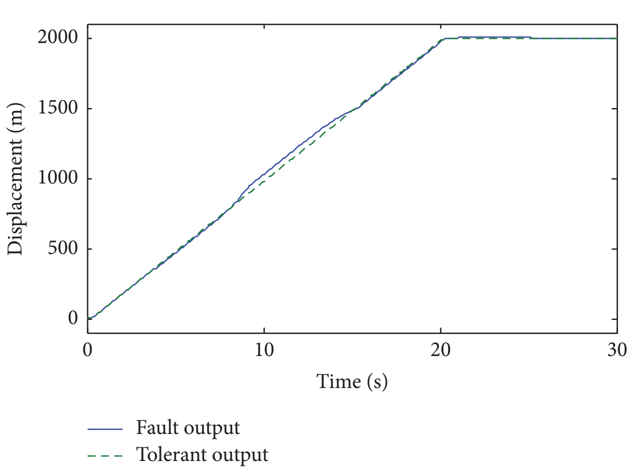


FIGURE 9: Displacement output with and without FTC.

faults disappear at 5 s and 9 s, the fault indicator returns to 0. It should be pointed out that the fault indicator will not change to 1 immediately especially when the constant deviation fault occurs at 12 s. Through the amplification of details, we find that it occurs at about 12.4 s due to the residual signal $\lambda(m)$ falling in the scope of $(\ln(TH_0), \ln(TH_1))$. That means the unreliability of FDD exists under this circumstance.

In order to verify the effectiveness of smooth and flexible switching strategy based on the reliability factor α, we compare it with the traditional switching based on sign function. The simulation result is showed in Figure 7. By zooming out the details, we can see that the traditional method acting at about 12.5 s has a certain delay and switches violently which corresponds to the fault indicator, while the method proposed in this paper based on a flexible switching strategy is smoother and more reliable.

Figures 8 and 9 show, respectively, the speed and position outputs with and without FTC based on a flexible switching. From Figure 8, we can see that when the sensor fails at different time in a closed loop control system without FTC, the output shows a level of oscillation, while when the FTC is implemented after a fault is detected, the output shows good stability and smoothness. It also verified the effectiveness of the proposed FTC.

6. Conclusions

This paper focuses on the fault detection and tolerant control of the speed sensor—incremental encoder—for an elevating stage control system. An AFTC method based on tracking differentiator is proposed. From the analysis and simulation, it is confirmed that (i) using the redundancy relationship between velocity and displacement signal in a dual closed loop system to construct a fault tolerant strategy is simple and convenient. (ii) Compared to the traditional DTD and the new MTD, the novel tracking differentiator design based on hyperbolic tangent function is effective. It has faster tracking speed and higher differential and tracking accuracy. Its filtering effects are also satisfactory. (iii) In implementing the fault tolerant switching strategy, the designed reliability factor α based on smooth function reduces the transient vibration and improves the reliability of FDD and realizes an integrated design for the reliability of FDD and the FTC.

The next problems to be solved are (i) the experimental verification and the engineering practice of the proposed method and (ii) from the perspective of the whole system, how to integrate the absolute encoder fault into the AFTC framework.

Appendix

Proof. In order to verify the theorem, we can rewrite (7) as follows:

$$\begin{aligned}\dot{x}_1(t) &= x_2(t),\\ \dot{x}_2(t) &= R^2 u\left(x_1(t) - v(t), \frac{x_2(t)}{R}\right).\end{aligned} \tag{A.1}$$

When the input signal is constant, $v(t) = c$, it can make variable substitution as the following:

$$
\begin{aligned}
t' &= \frac{t}{R}, \\
x_1(t') &= z_1(t) + c, \\
x_2(t') &= R \cdot z_2(t).
\end{aligned}
\tag{A.2}
$$

Then we have

$$
\begin{aligned}
dt' &= \frac{dt}{R}, \\
\dot{x}_1(t') &= \dot{z}_1(t) \cdot R = x_2(t') = z_2(t) \cdot R, \\
\dot{x}_2(t') &= R^2 \dot{z}_2(t) = R^2 u\left(x_1(t') - c, \frac{x_2(t')}{R}\right) \\
&= R^2 u(z_1(t), z_2(t)).
\end{aligned}
\tag{A.3}
$$

Obviously, it equals the next equations:

$$
\begin{aligned}
\dot{z}_1(t) &= z_2(t), \\
\dot{z}_2(t) &= u(z_1(t), z_2(t)).
\end{aligned}
\tag{A.4}
$$

That is the lemma. So it can be easily proved.

Next, considering the general situation when the input signal $v(t)$ is a bounded, integrable, and time varying function, $t \in [0, T]$, for a given scalar $\forall \varepsilon > 0$, there exists a continuous function $\varphi(t) \in C[0, T]$, satisfying:

$$
\int_0^T |v(t) - \varphi(t)| \, dt < \frac{\varepsilon}{2}. \tag{A.5}
$$

For this $\varphi(t)$, there also exists a series of simple function $\varphi_n(t)$, $n = 1, 2, \ldots$, which is uniform convergence to $\varphi(t)$. It means that there exists an integer N_0, when $M > N_0$, $|\varphi(t) - \varphi_M(t)| < \varepsilon/4T$. So we have the following equation:

$$
\begin{aligned}
\int_0^T |v(t) - \varphi_M(t)| \, dt &\leq \int_0^T |v(t) - \varphi(t)| \, dt \\
&\quad + \int_0^T |\varphi(t) - \varphi_M(t)| \, dt \\
&< \frac{\varepsilon}{2}.
\end{aligned}
\tag{A.6}
$$

As $\varphi(t)$ is continuous and $[0, T]$ is divided into limited subintervals $I_i, i = 1, 2, \ldots, m$, assume that $\varphi_M(t)$ is a constant in I_i. So for every subinterval, $\exists R_0 > 0$, when $R > R_0$, we have

$$
\int_{I_i} |x_1(t) - \varphi_M(t)| \, dt < \frac{\varepsilon}{2m}, \quad i = 1, 2, \ldots, m. \tag{A.7}
$$

It implies that $\int_0^T |x_1(t) - \varphi_M(t)| dt < \varepsilon/2$. Thus when $R > R_0$,

$$
\begin{aligned}
\int_0^T |x_1(t) - v(t)| \, dt &< \int_0^T |x_1(t) - \varphi_M(t)| \, dt \\
&\quad + \int_0^T |\varphi_M(t) - v(t)| \, dt < \varepsilon.
\end{aligned}
\tag{A.8}
$$

So $\lim_{R \to \infty} \int_0^T |x_1(t) - v(t)| dt = 0$. □

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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