Abstract—We investigate a novel adaptive fault-tolerant control method for time-varying failure in high-speed train computer systems and propose a fault model for such systems. First, the dynamics of high-speed train systems are analyzed and a multiple point-mass model is developed. When actuator outputs deviate from the expected value, a novel adaptive fault-tolerant control method based on Lyapunov stable theory is automatically implemented to compensate for the unknown fault effects and ensure system stability and performance. The effectiveness of the proposed approach is also confirmed through numerical simulations by using a train model similar to China Railways High-speed 5.

Index Terms—Fault-Tolerant Control; Adaptive Control; High-Speed Train Systems

I. INTRODUCTION

To date, fault-tolerant control is widely applied in various industries such as chemical engineering [1–4], nuclear engineering [5, 6], aerospace engineering [7, 8], and automotive systems [9]. The application of advanced fault-tolerant control technology is necessary for high-speed train systems.

A train operation control system generally uses two types of models, namely, single and multiple point-mass models. The single point-mass model assumes that the couplers among carriages are stiff and all carriages can be considered a united rigid body. Therefore, the single point-mass model uses a classical control method to design the cruise controller. Howlett [10–12] uses the Pontryagin principle to find the nature of the optimal strategy and applies this information to determine the precise optimal strategy. Khmelnitsky [13] develops a detailed program for traction and brake applications that minimizes the energy consumption during train movement along a given route in a given time. Wang [14] applies an iterative learning control theory into an automatic train operation system to enable the train to drive itself consistently with a given guidance trajectory (including the velocity and coordinate trajectories). Gao [15, 16] studies the one-level speed adjustment braking of an automatic train operation system. Song [17] investigates the automatic control problem of high-speed train systems under immeasurable aerodynamic drag.

Robust and adaptive control algorithms have been developed to ensure the high precision tracking of train position and velocity. Considering that the functions of the couplers and the relative velocity among adjacent vehicles are ignored, the controller based on the single point-mass model will cause the unstable motion of the system when carriages are connected by a flexible connector. Therefore, the multiple point-mass model assumes that a train, which is composed of locomotives and wagons (both referred to as carriages), is modeled as carriages connected by couplers. A dynamic model that explicitly reflects the interaction effects among vehicles is established by using the multiple point-mass Newton equations. Song [18, 19] investigates the position and velocity tracking control problem of high-speed trains with multiple vehicles connected by couplers. Lin [20] presents an analysis of the cruise control for high-speed trains. A train system is designed to be safe and reliable with high efficiency and fault tolerance. Output regulation with measurement feedback has been proposed to control heavy-haul trains. The objective of this approach is to regulate the train velocity to a prescribed speed profile. Chou [21] proposes a closed-loop cruise controller to minimize the running cost of heavy-haul trains equipped with electronically controlled pneumatic brake systems.

The rest of the paper is organized as follows. Section II introduces the plant model, which characterizes basic actuator failure, and the control objective. Section III derives an adaptive fault-tolerant control design when some actuators deviate from the expected value. Section IV presents the proposed adaptive fault-tolerant control method. Section V introduces the simulation. Section VI concludes.

II. DYNAMIC MODEL OF HIGH-SPEED TRAIN SYSTEMS

A carriage in high-speed train systems is subjected to the traction/brake force, adjoining internal-forces of carriages, the aerodynamic force, friction between train wheels and track, gravity force, and the curve resistance during train operation. Such carriage can be modeled as follows:
\[ m \ddot{x}_i(t) = \dot{\lambda}_u(t) - k^-(x_i(t) - x_{i-1}(t)) - b(\dot{x}_i(t) - \dot{x}_{i-1}(t)) \]
\[ -c_{w_i}(\sum_{j=1}^{i-1} m_j) - 9.98 \sin \theta m_i - 0.002 m_i d_i / R_i \]
\[ = \dot{\lambda}_u(t) - k^-(x_i(t) - x_{i-1}(t)) - b(\dot{x}_i(t) - \dot{x}_{i-1}(t)) \]
\[ -c_{w_i}(\sum_{j=1}^{i-1} m_j) - 9.98 \sin \theta m_i - 0.002 m_i d_i / R_i \]
\[ \dot{x}_i(t) = \dot{\lambda}_u(t) - k^-(x_i(t) - x_{i-1}(t)) - b(\dot{x}_i(t) - \dot{x}_{i-1}(t)) \]
\[ -c_{w_i}(\sum_{j=1}^{i-1} m_j) - 9.98 \sin \theta m_i - 0.002 m_i d_i / R_i \]
\[ \dot{x}_{i-1}(t) = \dot{\lambda}_u(t) - k^-(x_i(t) - x_{i-1}(t)) - b(\dot{x}_i(t) - \dot{x}_{i-1}(t)) \]
\[ -c_{w_i}(\sum_{j=1}^{i-1} m_j) - 9.98 \sin \theta m_i - 0.002 m_i d_i / R_i \]

By assuming a target speed, we derive the corresponding position, acceleration, and traction force:
\[ x_i(t) = x_0(t) + \Delta x_i(t) \]
\[ \dot{x}_i(t) = v_0(t) + \Delta \dot{x}_i(t) \]
\[ \ddot{x}_i(t) = a_0^i(t) + \Delta \ddot{x}_i(t) = \Delta \ddot{x}_i(t) \]
\[ u_i(t) = u_0^i(t) + \Delta u_i(t) \]

The ideal motion equations of high-speed train systems are as follows:
\[ u_i^0 = (c_0 + c_i v_0^2) m_i - c_i \dot{x}_i^0 (\sum_{j=1}^{i} m_j) \]
\[ u_i^0 = (c_0 + c_i v_0^2) m_i (i = 2, \cdots, n) \]

Eqs. (3), (4) and (5) will be transformed into the following:

\[ m_i \ddot{x}_i(t) + (c_i m_i + 2c_i v_0 \sum_{j=1}^{n} m_j) \Delta \dot{x}_i(t) - k^- \Delta x_i(t) \]
\[ + k^- \Delta x_i(t) - b \Delta \dot{x}_i(t) + b \Delta \dot{x}_i(t) = \lambda^* \Delta u_i(t) \]
\[ m_i \ddot{x}_i(t) + c_i m_i \dot{x}_i(t) + 2k^- \Delta x_i(t) \]
\[ - k^- \Delta x_i(t) - k^- \Delta x_{i+1}(t) + 2b \Delta \dot{x}_i(t) \]
\[ - b \Delta \dot{x}_i(t) = \lambda^* \Delta u_i(t) (i = 2, \cdots, n) \]

The standard state space form of the high-speed train systems can be transformed into the following equation:
\[ \dot{x}(t) = \tilde{A} x(t) + \tilde{B} u(t) \]
\[ y(t) = \tilde{C} x(t) \]
\[ x(t) = [\Delta x_1(t) \cdots \Delta x_t(t) \Delta \dot{x}_1(t) \cdots \Delta \dot{x}_t(t)]^T \]
\[ y(t) = [\Delta x_1(t) \cdots \Delta x_t(t) \Delta \dot{x}_1(t) \cdots \Delta \dot{x}_t(t)]^T \]

The target system will be:
\[ \dot{x}_0(t) = \tilde{A} x_0(t) + \tilde{B} \nu(t) \]
\[ y_0(t) = \tilde{C} x_0(t) \]

The control objective is \( \lim \epsilon \rightarrow 0,(e = x - \bar{x}_n) \).

During actuator faults, the high-speed train systems will not meet the requirements and safety standards. Therefore, we should adopt a fault-tolerant control to ensure train security in high-speed train systems with faults.

Let \( \bar{u}(t) \) be the fault input, where \( \Pi(t) = [\bar{u}_1, \bar{u}_2, \ldots, \bar{u}_n]^T, \)
\[ \bar{u}_j = \bar{u}_j f_j(t) \]
where \( \bar{u}_j \) is an unknown scalar, and \( f_j(t) \) is a known signal.

### III. CONTROL DESIGN

To develop adaptive control schemes for systems with unknown actuator failures, we should determine the appropriate controller structure and parameter for cases when system parameters and actuator failure parameters are known. When the fault parameters are known, the system will be stabilized by the following:
Let 
\[ \sigma = \text{diag} \{ \sigma_1, \sigma_2, \ldots, \sigma_m \} \]
\[ \sigma_j = \begin{cases} 1 & (u_j = \bar{u}_j) \\ 0 & (u_j = v_j) \end{cases} \]

When a known fault occurs, the original system is transformed into the following:
\[
\begin{align*}
\dot{x}(t) &= \begin{bmatrix} 0 & I \\ -A^T C & -A^T B \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0 \end{bmatrix} v(t) + \begin{bmatrix} 0 \\ A \end{bmatrix} \sigma(x(t) - v(t)) \\
\dot{\tilde{x}}(t) &= \begin{bmatrix} 0 & I \\ -A^T C & -A^T B \end{bmatrix} \tilde{x}(t) + \begin{bmatrix} 0 \\ \Lambda \end{bmatrix} K_i^T \left( x(t) - \tilde{x}(t) \right) \\
&\quad + \begin{bmatrix} 0 & 0 \\ \Lambda & 0 \end{bmatrix} \tilde{k}_j(t) + \begin{bmatrix} 0 \\ A \end{bmatrix} \sigma(x(t) - v(t))
\end{align*}
\]
and then the control parameters satisfying the following equation:
\[
\begin{align*}
\begin{bmatrix} 0 & I \\ -A^T C & -A^T B \end{bmatrix} + \sum_{j \neq j_p} \begin{bmatrix} 0 \\ \Lambda_j \end{bmatrix} K_i^T_j &= \begin{bmatrix} 0 \\ \Lambda_m \end{bmatrix} \\
\sum_{j \neq j_p} \begin{bmatrix} 0 \\ \Lambda_j \end{bmatrix} \tilde{k}_j(t) &= \begin{bmatrix} 0 \\ 0 \end{bmatrix}
\end{align*}
\]
and then fault system will be tracking the target system.

Now we adopt an adaptive control scheme for the system with unknown fault parameters. The direct adaptive fault-tolerant control will be expressed as follows:
\[
u(t) = K_i^T \begin{bmatrix} x(t) \\ \tilde{x}(t) \end{bmatrix} + K_i r(t) + \tilde{k}_j
\]

Define the parameter errors:
\[
\begin{align*}
\tilde{k}_j(t) &= K_j - K_i^T_j \\
\tilde{k}_{2j}(t) &= K_{2j} - K_{2i} \\
\tilde{k}_j(t) &= k_{2j} - k_i
\end{align*}
\]

The original system will be transformed into the follows:
\[
\begin{align*}
\dot{\tilde{\hat{x}}}(t) &= \begin{bmatrix} 0 & I \\ -A^T C & -A^T B \end{bmatrix} \tilde{\hat{x}}(t) + \begin{bmatrix} 0 \\ 0 \end{bmatrix} (I - \sigma) \\
&\quad + \begin{bmatrix} 0 & 0 \\ \Lambda & 0 \end{bmatrix} \sigma(x(t) - v(t))
\end{align*}
\]

We have the tracking error equation:
\[
\begin{align*}
\dot{\tilde{e}}(t) &= \begin{bmatrix} 0 & I \\ -A^T C & -A^T B \end{bmatrix} \tilde{e}(t) + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tilde{k}_j^T \tilde{\hat{x}}(t) \\
&\quad + \sum_{j \neq j_p} \begin{bmatrix} 0 \\ \Lambda_j \end{bmatrix} \tilde{k}_{2j}(t) + \sum_{j \neq j_p} \begin{bmatrix} 0 \\ \Lambda_j \end{bmatrix} \tilde{k}_j(t)
\end{align*}
\]
Consider the positive-definition equation:
\[
\begin{align*}
V(x, \tilde{K}_i, \tilde{K}_j, \tilde{k}_j) &= \begin{bmatrix} \tilde{e} \\ \tilde{e} \end{bmatrix} P \begin{bmatrix} \tilde{e} \\ \tilde{e} \end{bmatrix} + \sum_{j \neq j_p} \begin{bmatrix} 0 \\ \Lambda_j \end{bmatrix} \tilde{k}_j^T \tilde{\hat{x}}(t) \\
&\quad + \sum_{j \neq j_p} \begin{bmatrix} 0 \\ \Lambda_j \end{bmatrix} \tilde{k}_{2j}^T + \sum_{j \neq j_p} \begin{bmatrix} 0 \\ \Lambda_j \end{bmatrix} \tilde{k}_j(t)
\end{align*}
\]
where \( P \in \mathbb{R}^{2n \times 2n} \), \( P = P^T > 0 \) such that
\[
\begin{align*}
\begin{bmatrix} 0 & I \\ -A^T C & -A^T B \end{bmatrix} + \begin{bmatrix} 0 \\ \Lambda \end{bmatrix} \tilde{k}_j(t) &= \begin{bmatrix} 0 \\ 0 \end{bmatrix} \\
\sum_{j \neq j_p} \begin{bmatrix} 0 \\ \Lambda_j \end{bmatrix} \tilde{k}_j(t) &= \begin{bmatrix} 0 \\ 0 \end{bmatrix}
\end{align*}
\]
and then fault system will be tracking the target system.
The adaptive controller with adaptive laws applies to the system with actuator failures and guarantees that all closed-loop signals are bounded. The tracking error goes to zero as time goes to infinity.

IV. SIMULATION

In this section, we use the simulation results to verify the effectiveness of our proposed adaptive control schemes. The failure model is adopted as follows:

$$\tilde{u}_j = 5 \sin 0.2t \quad (\tilde{u}_j = 5, f_j(t) = \sin 0.2t)$$

$$f_{\text{act}} = 30s$$

Parameters of CRH5 are adopted. The parameters of the high-speed train are shown in the table 1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Implication</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>No. of carriages</td>
<td>8</td>
<td>null</td>
</tr>
<tr>
<td>w</td>
<td>No. of powered carriages</td>
<td>5</td>
<td>null</td>
</tr>
<tr>
<td>m_(i=1,2,4,7,8)</td>
<td>No. of powered carriages</td>
<td>8500</td>
<td>kg</td>
</tr>
<tr>
<td>m_(i=3,5,6)</td>
<td>Mass of powered carriages</td>
<td>8095</td>
<td>kg</td>
</tr>
<tr>
<td>c0</td>
<td>Mechanical resistance coefficient</td>
<td>5.2</td>
<td>N/kg</td>
</tr>
<tr>
<td>cv</td>
<td>Mechanical resistance coefficient</td>
<td>0.038</td>
<td>N/s/m/kg</td>
</tr>
<tr>
<td>ca</td>
<td>Aerodynamic drag coefficient</td>
<td>0.00112</td>
<td>N·s²/m²/kg</td>
</tr>
<tr>
<td>k</td>
<td>Elasticity coefficient</td>
<td>20×10⁶</td>
<td>N/m</td>
</tr>
<tr>
<td>b</td>
<td>Damping coefficient</td>
<td>5×10⁶</td>
<td>N·s/m/kg</td>
</tr>
<tr>
<td>umax</td>
<td>Maximum traction input</td>
<td>302</td>
<td>kN</td>
</tr>
<tr>
<td>umin</td>
<td>Minimum traction input</td>
<td>205</td>
<td>kN</td>
</tr>
</tbody>
</table>

Figure 1. Position tracking error of the 1th carriage in high-speed train systems

Figure 2. Position tracking error of the 2th carriage in high-speed train systems

Figure 3. Position tracking error of the 3 th carriage in high-speed train systems

Figure 4. Position tracking error of the 4 th carriage in high-speed train systems

Figure 5. Position tracking error of the 5 th carriage in high-speed train systems

Figure 6. Position tracking error of the 6 th carriage in high-speed train systems

Figure 7. Position tracking error of the 7 th carriage in high-speed train systems

Figure 8. Position tracking error of the 8 th carriage in high-speed train systems

Figure 9. Velocity tracking error of the 1th carriage in high-speed train systems
With two fading actuators (motor 1 and motor 7), the fault-tolerant control algorithms (19), (20) and (21) are tested and the results are presented, one can observe that the proposed fault-tolerant control scheme performs well even if some of the actuators lose their effectiveness during the system operation. In a fault system with an adaptive tracking controller, the actual position can track the target position well (Figure 1-8). The actual velocity in the fault system can track the target velocity satisfactorily and satisfy the system control objectives (Figure 9-16). The design parameters of the controller can be set quite arbitrarily without the need for consistently tuning by the designer for tracking stability, although some trade-off is needed to accommodate the tracking precision and the magnitude of the control effort. It is shown in the Fig.1-8, that the fault is occurred at 30s and the position tracking error of the high-speed train systems does not change much. And Correspondingly, the velocity tracking error of the high-speed systems in Fig. 9-16 also converges to zero. It is shown that the performance of the fault high-speed train systems is very excellent. But we can see in the Fig.1-16 the position tracking error and velocity tracking error do not converge to zero exactly, because the coefficient of elasticity $k^-$ we used is the lower bound of the actual value $k^-$.

V. CONCLUSION

The position and velocity tracking control problems of high-speed train systems have been tested in the presence of actuator time-varying failures. A novel adaptive state feedback controller has been constructed to compensate for unknown fault effects automatically. The proposed algorithm guarantees the stability, asymptotic position, and velocity tracking of high-speed train systems. The simulation results demonstrate the efficiency of the proposed algorithms and their applicability to the operation control of trains.

REFERENCES


