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Citation for published version

Mao, Zehui and Tao, Gang and Jiang, Bin and Yan, Xinggang and Zhong, Maiying (2017) Adaptive Position Tracking Compensation for High-Speed Trains with Actuator Failures. In: 20th World Congress of the International Federation of Automatic Control (IFAC), 9-14 July 2017, Toulouse, France.

DOI

https://doi.org/10.1016/j.ifacol.2017.08.1835

Link to record in KAR

http://kar.kent.ac.uk/61781/

Document Version

Author's Accepted Manuscript

Adaptive Position Tracking Compensation for High-Speed Trains with Actuator Failures ⋆

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Abstract: In this paper, an adaptive failure compensation is proposed for high-speed trains with traction system actuator failures to achieve the position tracking. To deal with the time-varying parameters of the train motion dynamics, the piecewise constant model is introduced to describe the train dynamics with variable parameters. For the system with actuator failures, the adaptive controller with the adaptive laws is designed to achieve the position tracking, in the presence of the system piecewise constant parameters and actuator failure parameters which are unknown. Simulation results on a high-speed train model are presented to illustrate the performance of the developed adaptive actuator failure compensation control scheme.

Keywords: Actuator failures, adaptive control, failure compensation, high-speed train.

1. INTRODUCTION

Due to their fast and high loading capacities, high-speed trains have become more popular. For the past few years, a considerable number of studies have been focused on control design for the train systems (see, for example, Dong et al. (2010), Song et al. (2011), Zhang et al. (2014). For this kind of large scale transportation systems, the safety and reliability are important factors. The failures may deteriorate the train performance severely, resulting in time delay or cancellation of the other trains. Therefore, it is crucial for the traction system of high-speed trains to study the effective failure compensation technologies.

During the past years, some results on fault diagnosis and fault-tolerant control for high-speed trains have been obtained, see, for example Guzinski et al. (2009), Song et al. (2011), Wang et al. (2016). Most of the existing work uses the motion dynamic model with constants parameters, or the variable parameters with known upper bounds. These constants or bounded variable parameters cannot represent the characteristics of the system dynamics well, which motivates the research to derive a new suitable model. A new piecewise constant model with unknown parameters is presented in this paper to describe the high-speed train dynamics.

On the other hand, although there exists many results about the fault-tolerant control, see Blanke et al. (2003)-Shen et al. (2014). In these results, the parameters of the plants are assumed either known or unknown but are modeled as unknown inputs with bounds. Thus, these methods cannot be used in the piecewise constants model of the high-speed trains with the unknown failures. Due to the characterise that the adaptive techniques can deal with the unknown parameters and achieve good tracking performance (see Tao et al. (2014), Tao et al. (2014)), the adaptive compensation can be used to solve the fault-tolerant control problem of the high-speed trains.

This paper is focused on the adaptive position tracking compensation problem for the high-speed trains with traction system actuator failures. A piecewise constant model is introduced to describe the motion dynamic of the high-speed train with its variable parameters. The adaptive failure compensation controller design procedure is presented to achieve the train position tracking. The rest of this paper is organized as follows: In Section II, the dynamical model of high-speed trains are introduced, and the actuator failure compensation problem is formulated. In Section III, the failure compensation schemes for the piecewise constant parameter systems with unknown pa-

⋆ This work was supported in part by the National Natural Science Foundation of China under Grant 61490703, Grant 61573180 and Grant 61374130.

rameterized failures, are developed. In Section IV, simulations are presented to verify the effectiveness of the failure compensation schemes. Finally, some conclusions are given in Section V.

2. PROBLEM FORMULATION

In this section, we will introduce the dynamic model of high-speed trains and the model of traction system actuator failures. Further, the objective of this work and the design issues for adaptive control and failure compensation are formulated.

2.1 Longitudinal Motion Dynamic Model

By Newton's law, the longitudinal motion dynamics of a train can be described as Guzinski et al. (2009):

$$M(t)\ddot{x}(t) = F(t) - F_r(t) - F_g(t) - F_c(t), \qquad (1)$$

where $x(t)$ is the displacement of the train, $M(t)$ is the mass of the train, $F(t)$ is the traction force, $F_r(t)$ is the general resistance, $F_g(t)$ is the force caused by motion on the grade, $F_c(t)$ is the force caused by motion on the curve. The force $F(t)$ acting on the train, is generated by the traction system to achieve the tractive effort or dynamic braking, which can represent the action on the train to reduce motion during the application of the brakes.

As modeled in AREMA (1999), the general resistance $F_r(t)$ is approximated by a quadratic function, i.e., the Davis equation:

$$F_r(t) = a_r(t) + b_r(t)v(t) + c_r(t)v^2(t), \qquad (2)$$

where $M(t)$ is the mass of the train, $v(t)$ is the speed of the train; $a_r(t)$ defines the train's rolling resistance component, $b_r(t)$ defines the train's linear resistance, $c_r(t)$ defines the train's nonlinear resistance.

From Garg (1984), the grade resistance force $F_g(t)$ and the curvature force $F_c(t)$ are modeled as

$$F_g(t) = M(t) g \sin\theta(t), \qquad (3)$$
$$F_c(t) = 0.004D(t)M(t), \qquad (4)$$

where $\theta(t)$ is the slope angle of the current track. $D(t)$ is the degree of curvature and can be calculated by $D(t) = 0.5d_w/R(t)$, with d_w being the distance between the front and rare wheels of the train (the wheelbase length, a constant for a certain train,), and $R(t)$ being the curve radius (a constant for a certain curvature track).

According to the analysis in Mao et al. (2015), the longitudinal motion dynamics of a train can be approximated by a piecewise constant model.

2.2 Piecewise Dynamic Model

With $m(t) = \dfrac{1}{M(t)}$, $a(t) = \dfrac{a_r(t)}{M(t)}$, $b(t) = \dfrac{b_r(t)}{M(t)}$, $c(t) = \dfrac{c_r(t)}{M(t)}$ and $\vartheta(t) = \sin\theta(t)$, equation (1) can be rewritten as

$$\ddot{x}(t) = m(t)F(t) - \big(a(t) + b(t)\dot{x}(t) + c(t)\dot{x}^2(t)\big) \\ -g\vartheta(t) - 0.004D(t), \qquad (5)$$

where $m(t)$, $a(t)$, $b(t)$, $c(t)$, $\vartheta(t)$, and $D(t)$ are piecewise constants and are dependent on the displacement x and velocity $\dot{x}$ of the train.

Define Ω as the region for all possible system states $x(t)$ and $\dot{x}(t)$ during the train operation, with its l subregions Ω_i, $i = 1, \ldots, l$. The values of $(m(t), a(t), b(t), c(t), \vartheta(t), D(t))$ are determined as $(m(t), a(t), b(t), c(t), \vartheta(t), D(t)) = (m_i, a_i, b_i, c_i, \vartheta_i, D_i)$, if $(x(t), \dot{x}(t)) \in \Omega_i$, where $i = 1, \ldots, l$, m_i, a_i, b_i, c_i, ϑ_i, and D_i are unknown constants. Due to the fact that $x(t)$ and $\dot{x}(t)$ are available, the time instants when $(x(t), \dot{x}(t))$ jumps from one region to another are known.

To describe the piecewise constants of the parameters in equation (5), the indicator functions $\chi_i(t)$ are introduced as follows:

$$\chi_i(t) = \begin{cases} 1, \text{ if } \ (x(t), \dot{x}(t)) \in \Omega_i, \\ 0, \text{ otherwise}, \end{cases} \qquad (6)$$

$$\sum_{i=1}^{l} \chi_i(t) = 1, \quad \chi_p(t)\chi_q(t) = 0, \quad \text{for} \quad p \neq q. \qquad (7)$$

It is assumed that there do not exist the common boundary, i.e., $(x(t), \dot{x}(t))$ only belongs to one region. Since the information about $(x(t), \dot{x}(t)) \in \Omega_i$ is available, the functions $\chi_i(t)$ defined in (6) are known.

Let $x_1 = x$ and $x_2 = \dot{x}$. The longitudinal motion dynamics (5) can be expressed as

$$\dot{x}_1(t) = x_2(t), \qquad (8)$$
$$\dot{x}_2(t) = m(t)F(t) - a(t) - b(t)x_2(t) - c(t)x_2^2(t) \\ -g\vartheta(t) - 0.004D(t), \qquad (9)$$

where

$$m(t) = \sum_{i=1}^{l} m_i\chi_i(t), \quad a(t) = \sum_{i=1}^{l} a_i\chi_i(t), \qquad (10)$$

$$b(t) = \sum_{i=1}^{l} b_i\chi_i(t), c(t) = \sum_{i=1}^{l} c_i\chi_i(t), \qquad (11)$$

$$\vartheta(t) = \sum_{i=1}^{l} \vartheta_i\chi_i(t), \quad D(t) = \sum_{i=1}^{l} D_i\chi_i(t), \qquad (12)$$

with m_i, a_i, b_i, c_i, ϑ_i, and D_i being unknown constants, and $\chi_i(t)$ being the indicator functions defined in (6).

2.3 Actuator Failure Model

This paper is focused on dealing with the failures of actuators, which can lead to the traction force $F(t)$ abnormal. We consider there are n motors in a train. So, the resultant traction force $F(t)$ is the sum of the forces F_j, $j = 1, \ldots, n$, generated from the jth motor:

$$F(t) = \sum_{j=1}^{n} F_j(t). \qquad (13)$$

The actuator failures can be modeled by

$$F_j(t) = \bar{F}_j(t) = \bar{F}_{j0} + \sum_{\rho=1}^{s_j} \bar{F}_{j\rho} f_{j\rho}(t), \quad t \geq t_j, \tag{14}$$

for some $j \in \{1, 2, \ldots, n\}$. Here, the failure occurring time instant t_j, failure index j, constants $\bar{F}_{j0}$ and $\bar{F}_{j\rho}$, are unknown, while the basis signals $f_{j\rho}(t)$ are known, and s_j are the number of the basis signals of the jth actuator failure.

From (14), the input of system (8)-(9) can be rewritten as

$$F(t) = \sum_{j=1}^{n} \left(\sigma_j \nu_j(t) + (1 - \sigma_j) \bar{F}_j(t) \right), \tag{15}$$

where $\nu_j(t)$ is the applied control signal to be designed, and σ_j is the actuator failure pattern parameter with

$$\sigma_j = \sigma_j(t) = \begin{cases} 0, & \text{if the } j\text{th actuator fails,} \\ 1, & \text{otherwise.} \end{cases} \tag{16}$$

There are n actuators in a train and up to $\bar{n}$ unknown actuator failures ($\bar{n} < n$), that is, during the train operation, any $\bar{n}$ of the n actuators may fail. When an actuator fails, the failure time and failure parameters are unknown. For the adaptive actuator failure compensation problem of the high-speed train, the basic assumption is given as: (A1) for any up to $\bar{n}$ actuators fail, the remaining healthy actuators can still achieve the desired control objective.

Since the actuators in the power units use the same control signal, it follows from (15) and (14) that the system input can be expressed by

$$F(t) = k_\nu \nu_0(t) + \xi^T \varpi(t), \tag{17}$$

$$\text{for} \quad j = 1, \ldots, n, \quad \xi = [\xi_1^T, \xi_2^T, \ldots, \xi_n^T]^T, \tag{18}$$

$$\xi_j = [\bar{F}_{j0}, \quad \bar{F}_{j1}, \ldots, \bar{F}_{js_j}]^T \in R^{s_j+1}, \tag{19}$$

$$\begin{aligned} \varpi(t) = [1, f_{11}(t), \ldots, f_{1s_1}(t), \ldots, 1, f_{j1}(t), \ldots, f_{js_j}(t), \\ \ldots, 1, f_{n1}(t), \ldots, f_{ns_n}(t)]^T, \end{aligned} \tag{20}$$

where $\nu_0(t)$ is a designed control signal, and k_ν is the actuator failure pattern parameter with ξ and $\varpi(t)$ to determine which actuators and what kind of failures occur. The parameter k_ν only takes one integer in the interval $[n - \bar{n}, n]$ to respect the different failures.

Objective. The objective of this paper is to develop an adaptive failure compensation scheme for high-speed trains described by (8), (9), with unknown friction parameters modeled in (10), (12), and unknown actuator failures modeled in (17)-(20), to guarantee the system stability and asymptotic tracking properties even in the presence of actuator failures.

For the high-speed train dynamic model with unknown actuator failures, there are two kind of parameter variations: (i) unknown values with known changing time caused by system mode changes; (ii) unknown values with unknown changing time caused by actuator failure changes. The designed adaptive failure compensation controller should handle these two kinds of variations, simultaneously.

3. ADAPTIVE FAILURE COMPENSATION CONTROLLER DESIGN

For high-speed train, the controller is designed for Distance-To-Go (DTG) curve. In this section, we will propose a failure compensation controller to guarantee the closed-loop system stable and the state $x_1(t)$ to track the desired curve $x_m(t)$. The design procedure is as follows:

Step 1: Let the tracking error be $z_1(t) = x_1(t) - x_m(t)$, and introduce $z_2(t) = x_2(t) - \alpha_1(t)$, where $\alpha_1(t)$ is a function to be designed. Then, from (8), we get

$$\begin{aligned} \dot{z}_1(t) &= \dot{x}_1(t) - \dot{x}_m(t) \\ &= z_2(t) + \alpha_1(t) - \dot{x}_m(t) \end{aligned} \tag{21}$$

Choosing the design function $\alpha_1(t)$ as

$$\alpha_1(t) = -r_1 z_1(t) + \dot{x}_m(t), \quad r_1 > 0 \tag{22}$$

and considering the first partial positive definite function

$$V_1 = \frac{1}{2} z_1^2(t) \tag{23}$$

We derive the time derivative of V_1 as

$$\begin{aligned} \dot{V}_1 &= z_1(t) \dot{z}_1(t) \\ &= z_1(t) \left(z_2(t) - r_1 z_1(t) + \dot{x}_m(t) - \dot{x}_m(t) \right) \\ &= -r_1 z_1^2(t) + z_1(t) z_2(t). \end{aligned} \tag{24}$$

Step 2: From $z_2(t) = x_2(t) - \alpha_1(t)$ and (9), we obtain

$$\begin{aligned} \dot{z}_2(t) &= \dot{x}_2(t) - \dot{\alpha}_1(t) \\ &= \sum_{i=1}^{l} \left(m_i \chi_i(t) (k_\nu \nu_0(t) + \xi^T \varpi(t)) - a_i \chi_i(t) \right. \\ &\quad - b_i \chi_i(t) x_2(t) - c_i \chi_i(t) x_2^2(t) \\ &\quad \left. - g \vartheta_i \chi_i(t) - 0.004 D_i \chi_i(t) \right) - \dot{\alpha}_1(t) \end{aligned} \tag{25}$$

Now, (21) and (25) can be viewed to be stabilized by $\alpha_1(t)$ given in (22) with respect to the Lyapunov function

$$\begin{aligned} V_2 = V_1 + \frac{1}{2} z_2^2(t) + \sum_{i=1}^{l} \frac{1}{2} \frac{m_i}{\gamma_{k\nu}} \tilde{\rho}_{k\nu}^2(t) \\ + \sum_{i=1}^{l} \frac{m_i}{2} \gamma_\xi^{-1} \tilde{\xi}^T(t) \tilde{\xi}(t) + \sum_{i=1}^{l} \frac{1}{2} \left(\gamma_{ai}^{-1} \tilde{a}_i^2(t) \right. \\ + \Gamma_{bi}^{-1} \tilde{b}_i^2(t) + \gamma_{ci}^{-1} \tilde{c}_i^2(t) + \gamma_{\vartheta i}^{-1} \tilde{\vartheta}_i^2(t) \\ \left. + \gamma_{Di}^{-1} \tilde{D}_i^2(t) + \frac{m_i}{\gamma_{mi}} \tilde{\rho}_i^2(t) \right), \end{aligned} \tag{26}$$

where $\gamma_{k\nu}$, γ_ξ,γ_{ai}, γ_{bi}, γ_{ci}, $\gamma_{\vartheta i}$, γ_{Di} and γ_{mi} are positive constants. $\tilde{\xi}(t)$, $\tilde{a}_i(t)$, $\tilde{b}_i(t)$, $\tilde{c}_i(t)$, $\tilde{\vartheta}_i(t)$, and $\tilde{D}_i(t)$ are defined as $\tilde{\xi}(t) = \xi - \hat{\xi}(t)$, $\tilde{a}_i(t) = a_i - \hat{a}_i(t)$, $\tilde{b}_i(t) = b_i - \hat{b}_i(t)$, $\tilde{c}_i(t) = c_i - \hat{c}_i(t)$, $\tilde{\vartheta}_i(t) = \vartheta_i - \hat{\vartheta}_i(t)$, $\tilde{D}_i(t) = D_i - \hat{D}_i(t)$, with $\hat{\xi}(t)$, $\hat{a}_i(t)$, $\hat{b}_i(t)$, $\hat{c}_i(t)$, $\hat{\vartheta}_i(t)$, $\hat{D}_i(t)$ being the estimates of ξ, a_i, b_i, c_i, ϑ_i, and D_i. $\tilde{\rho}_{k\nu}(t) = \rho_{k\nu} - \hat{\rho}_{k\nu}(t)$, $\tilde{\rho}_i(t) = \rho_i - \hat{\rho}_i(t)$, $\hat{\rho}_i(t)$ are the estimate of $\rho_{k\nu} = \frac{1}{k_\nu}$ and $\rho_i = \frac{1}{m_i k_\nu}$, respectively.

Let such time intervals be (T_p, T_{p+1}), $p = 0, 1, \ldots, \mathcal{M}$, that is, for $t \in (T_p, T_{p+1})$, the actuator failure pattern is fixed and the parameters in (17) are constant. Hence, the positive definite function V_2 is continuous and differentiable on the time intervals (T_p, T_{p+1}).

So the time derivative of V_2 is

$$\begin{aligned}
&\dot{V}_2 \\
&= -r_1 z_1^2(t) + z_1(t)z_2(t) + z_2\dot{z}_2(t) + \sum_{i=1}^{l} \frac{m_i}{\gamma_{k\nu}} \tilde{\rho}_{k\nu}(t)\dot{\hat{\rho}}_{k\nu}(t) \\
&\quad + \sum_{i=1}^{l} m_i \gamma_\xi^{-1} \tilde{\xi}^T(t)\dot{\hat{\xi}}(t) + \sum_{i=1}^{l} \big(\gamma_{ai}^{-1}\tilde{a}_i(t)\dot{\hat{a}}_i(t) \\
&\quad + \gamma_{bi}^{-1}\tilde{b}_i(t)\dot{\hat{b}}_i(t) + \gamma_{ci}^{-1}\tilde{c}_i(t)\dot{\hat{c}}_i(t) + \gamma_{\vartheta i}^{-1}\tilde{\vartheta}_i(t)\dot{\hat{\vartheta}}_i(t) \\
&\quad + \gamma_{Di}^{-1}\tilde{D}_i(t)\dot{\hat{D}}_i(t) + \frac{m_i}{\gamma_{mi}}\tilde{\rho}_i(t)\dot{\hat{\rho}}_i(t)\Big) \\
&= -r_1 z_1^2(t) + z_2(t)(x_1(t) - x_m(t)) \\
&\quad + z_2(t)\sum_{i=1}^{l}\Big(m_i\chi_i(t)(k_\nu \nu_0(t) + \hat{\xi}^T\varpi(t)) - \hat{a}_i\chi_i(t) \\
&\quad - \hat{b}_i\chi_i(t)x_2(t) - \hat{c}_i\chi_i(t)x_2^2(t) - g\hat{\vartheta}_i\chi_i(t) - 0.004\hat{D}_i\chi_i(t)\Big) \\
&\quad + z_2(t)(r_1(\dot{x}_1(t) - \dot{x}_m(t)) - \ddot{x}_m(t)) + \sum_{i=1}^{l}\frac{m_i}{\gamma_{k\nu}}\tilde{\rho}_{k\nu}(t)\dot{\hat{\rho}}_{k\nu}(t) \\
&\quad + \sum_{i=1}^{l} m_i\gamma_\xi^{-1}\tilde{\xi}^T(t)(\dot{\hat{\xi}}(t) - \gamma_\xi z_2(t)\varpi(t)) \\
&\quad + \sum_{i=1}^{l}\Big(\gamma_{ai}^{-1}\tilde{a}_i(t)(\dot{\hat{a}}_i(t) + \gamma_{ai}z_2(t)\chi_i(t)) \\
&\quad + \gamma_{bi}^{-1}\tilde{b}_i(t)(\dot{\hat{b}}_i(t) + \gamma_{bi}z_2(t)\chi_i(t)x_2(t)) \\
&\quad + \gamma_{ci}^{-1}\tilde{c}_i(t)(\dot{\hat{c}}_i(t) + \gamma_{ci}z_2(t)\chi_i(t)x_2^2(t)) \\
&\quad + \gamma_{\vartheta i}^{-1}\tilde{\vartheta}_i(t)(\dot{\hat{\vartheta}}_i(t) + \gamma_{\vartheta i}z_2(t)\chi_i(t)g) \\
&\quad + \gamma_{Di}^{-1}\tilde{D}_i(t)(\dot{\hat{D}}_i(t) + \gamma_{Di}z_2(t)\chi_i(t)0.004) \\
&\quad + \frac{m_i}{\gamma_{mi}}\tilde{\rho}_i(t)\dot{\hat{\rho}}_i(t)\Big)
\end{aligned} \tag{27}$$

Choose adaptive law for $\hat{\xi}(t)$, $\hat{a}_i(t)$, $\hat{b}_i(t)$, $\hat{c}_i(t)$, $\hat{\vartheta}_i(t)$, $\hat{D}_i(t)$ as

$$\dot{\hat{\xi}}(t) = \gamma_\xi z_2(t)\varpi(t) \tag{28}$$
$$\dot{\hat{a}}_i(t) = -\gamma_{ai}z_2(t)\chi_i(t) \tag{29}$$
$$\dot{\hat{b}}_i(t) = -\gamma_{bi}z_2(t)\chi_i(t)x_2(t) \tag{30}$$
$$\dot{\hat{c}}_i(t) = -\gamma_{ci}z_2(t)\chi_i(t)x_2^2(t) \tag{31}$$
$$\dot{\hat{\vartheta}}_i(t) = -\gamma_{\vartheta i}z_2(t)\chi_i(t)g \tag{32}$$
$$\dot{\hat{D}}_i(t) = -\gamma_{Di}z_2(t)\chi_i(t)0.004 \tag{33}$$

Then the derivative of V_2 can be expressed as

$$\begin{aligned}
&\dot{V}_2 \\
&= -r_1 z_1^2(t) + z_2(t)\Big(\eta(t) + \sum_{i=1}^{l}(m_i\chi_i(t)k_\nu\nu_0(t) \\
&\quad + m_i\chi_i(t)\hat{\xi}\varpi(t) - \zeta_i(t)\chi_i(t))\Big) \\
&\quad + \sum_{i=1}^{l}\frac{m_i}{\gamma_{k\nu}}\tilde{\rho}_{k\nu}(t)\dot{\hat{\rho}}_{k\nu}(t) + \sum_{i=1}^{l}\frac{m_i}{\gamma_{mi}}\tilde{\rho}_i(t)\dot{\hat{\rho}}_i(t) \\
&= -r_1 z_1^2(t) + z_2(t)\sum_{i=1}^{l} m_i k_\nu\Big(\chi_i(t)\nu_0(t) + \rho_{k\nu}\chi_i(t)\hat{\xi}\varpi(t) \\
&\quad - \rho_i\zeta_i(t)\chi_i(t) + \rho_i\chi_i(t)\eta(t)\Big) + \sum_{i=1}^{l}\frac{m_i}{\gamma_{k\nu}}\tilde{\rho}_{k\nu}(t)\dot{\hat{\rho}}_{k\nu}(t) \\
&\quad + \sum_{i=1}^{l}\frac{m_i}{\gamma_{mi}}\tilde{\rho}_i(t)\dot{\hat{\rho}}_i(t) \\
&= -r_1 z_1^2(t) + z_2(t)\sum_{i=1}^{l} m_i k_\nu\Big(\chi_i(t)\nu_0(t) + \rho_{k\nu}\chi_i(t)\hat{\xi}\varpi(t) \\
&\quad - \rho_i\zeta_i(t)\chi_i(t) + \rho_i\chi_i(t)\eta(t) + \rho_i r_2 z_2(t)\Big) - r_2 z_2^2(t) \\
&\quad + \sum_{i=1}^{l}\frac{m_i}{\gamma_{k\nu}}\tilde{\rho}_{k\nu}(t)\dot{\hat{\rho}}_{k\nu}(t) + \sum_{i=1}^{l}\frac{m_i}{\gamma_{mi}}\tilde{\rho}_i(t)\dot{\hat{\rho}}_i(t)
\end{aligned}$$

where $r_2 > 0$, $\eta(t) = x_1(t) - x_m(t) + r_1(\dot{x}_1(t) - \dot{x}_m(t)) - \ddot{x}_m(t)$, $\zeta_i(t) = \hat{a}_i + \hat{b}_i x_2(t) + \hat{c}_i x_2^2(t) + g\hat{\vartheta}_i + 0.004\hat{D}_i$.

The controller $\nu_0(t)$ should be

$$\begin{aligned}
\nu_0(t) = -\hat{\rho}_{k\nu}(t)\hat{\xi}\varpi(t) + \sum_{i=1}^{l}\Big(&\hat{\rho}_i\zeta_i(t)\chi_i(t) \\
&- \hat{\rho}_i\eta(t)\chi_i(t) - \hat{\rho}_i r_2 z_2(t)\chi_i(t)\Big)
\end{aligned} \tag{34}$$

Then the adaptive law for $\hat{\rho}_{k\nu}(t)$ and $\hat{\rho}_i(t)$ are chosen as

$$\dot{\hat{\rho}}_{k\nu}(t) = -\gamma_{k\nu}z_2(t)\hat{\xi}^T(t)\varpi(t) \tag{35}$$
$$\dot{\hat{\rho}}_i(t) = -\gamma_{mi}z_2(t)(\zeta_i(t) - \eta(t) - r_2 z_2(t))\chi_i(t) \tag{36}$$

Further, it has that

$$\dot{V}_2 = -r_1 z_1^2(t) - r_2 z_2^2(t) \tag{37}$$

It should be noted that the piecewise constant parameters, also with the failure parameters change their values, during the system operation. Then, we should analysis the unknown parameter changes.

As in Tao et al. (2014), let (T_p, T_{p+1}), $p = 0, 1, \ldots, \mathcal{M}$, with $T_0 = 0$, be time intervals. During these time intervals, the actuator failure pattern is fixed, which means that the actuators only fail at time T_p, for $p = 0, 1, \ldots, \mathcal{M}$. Under Assumption (A1), we have $\mathcal{M} \le \bar{n}$ and $T_{\mathcal{M}+1} = \infty$. At time $T_{\bar{p}}$, $\bar{p} = 0, 1, \ldots, \mathcal{M}$, the unknown parameters $\rho_{k\nu}$, ρ_i and ξ, change their values, due to the changes of the failure parameters k_ν and ξ. For the piecewise constant model (8)-(9), let $\{T_q\}_{q=1}^{\infty}$ denote the known time instants at which (8)-(9) switches between modes. It should be noted that the actuator failure time T_p is unknown, but switching mode time T_q is known. Then, there are two possible cases depending on the actuator failure time T_p and T_{p+1}.

(i) $T_{q-1} < T_p < T_q$, $T_{q-1} < T_{p+1} < T_q$: The actuator failures occur before the system (8)-(9) switches mode. Then, at time $T_{\bar{p}}$, $\bar{p} = 0, 1, \ldots, \mathcal{M}$, the unknown parameters $\rho_{k\nu}$, ρ_i ξ^*, a_i, b_i, c_i, ϑ_i and D_i, change their values during the time intervals (T_{q-1}, T_q), such that

$$\rho_{k\nu} = \rho_{k\nu(p)}, \quad \rho_i = \rho_{i(p)}, \quad \xi = \xi_{(p)}, \quad a_i = a_{i(p)},$$
$$b_i = b_{i(p)}, \quad c_i = c_{i(p)}, \quad \vartheta_i = \vartheta_{i(p)}, \quad D_i = D_{i(p)},$$

for $t \in (T_p, T_{p+1})$, $p = 0, 1, \ldots, \mathcal{M}$.

(ii) $T_{q-1} < T_p < T_q$, $T_q < T_{p+1}$: The actuator failures occur after the system (8)-(9) switches mode. Then, at time $T_{\bar{q}}$, $\bar{q} = 0, 1, \ldots, \infty$, the unknown plant model parameters change their values during the time intervals (T_{q-1}, T_{p+1}), such that

$$\rho_{k\nu} = \rho_{k\nu(p)}, \quad \rho_i = \rho_{i(p)}, \quad \xi = \xi_{(p)}, \quad a_i = a_{i(p)},$$
$$b_i = b_{i(p)}, \quad c_i = c_{i(p)}, \quad \vartheta_i = \vartheta_{i(p)}, \quad D_i = D_{i(p)},$$

and

$$\rho_{k\nu} = \rho_{k\nu(p)}, \quad \rho_{i+1} = \rho_{i+1(p)}, \quad \xi = \xi_{(p)},$$
$$a_{i+1} = a_{i+1(p)}, \quad b_{i+1} = b_{i+1(p)}, \quad c_{i+1} = c_{i+1(p)},$$
$$\vartheta_{i+1} = \vartheta_{i+1(p)}, \quad D_{i+1} = D_{i+1(p)},$$

Stability Analysis. For the function V_2, the term (containing $\tilde{\rho}_{k\nu}$ and $\tilde{\xi}$) about the failures is different from the term (last term, containing $\tilde{a}_i$, $\tilde{b}_i$, $\tilde{c}_i$, $\tilde{\vartheta}_i$, $\tilde{D}_i$ and $\tilde{\rho}_i$,) about the model parameters, because the switches of the failures are achieved via the matching condition instead of the indicator functions $\chi_i(t)$ in (6). Also, $V_2(\cdot)$ as a function of t is not continuous, because , $\rho_{k\nu}$, ξ, a_i, b_i, c_i, ϑ_i, D_i, ρ_i, are piecewise constant parameters. With the estimation errors $z_1(t)$, $z_2(t)$ and the adaptive laws in (28)-(33) and (35)-(36), the time derivative of V_2 for $t \in (T_p, T_{p+1})$, $p = 0, 1, \ldots, \mathcal{M}$, becomes

$$\dot{V}_2 = -r_1 z_1^2(t) - r_2 z_2^2(t) \tag{38}$$

Since there are only a finite number of failures in the system, $V_2(T_{\mathcal{M}})$ is finite, and, from

$$\dot{V}_2 = -r_1 z_1^2(t) - r_2 z_2^2(t) \le 0, \quad t \in (T_{\mathcal{M}}, \infty), \tag{39}$$

that is, $z_1(t) = x_1(t) - x_m(t)$, $z_2(t) = x_2(t) - \alpha_1(t)$, $\xi - \hat{\xi}(t)$, $a_i - \hat{a}_i(t)$, $b_i - \hat{b}_i(t)$, $c_i - \hat{c}_i(t)$, $\vartheta_i - \hat{\vartheta}_i(t)$, $D_i - \hat{D}_i(t)$, $\rho_{k\nu} - \hat{\rho}_{k\nu}(t)$, $\rho_i - \hat{\rho}_i(t)$, are bounded, and so are $z_1(t)$, $\hat{\xi}(t)$, $\hat{a}_i(t)$, $\hat{b}_i(t)$, $\hat{c}_i(t)$, $\hat{\vartheta}_i(t)$, $\hat{D}_i(t)$, $\hat{\rho}_{k\nu}(t)$ and $\hat{\rho}_i(t)$. From (22), $\alpha_1(t)$ is bounded, so is $x_2(t)$. Then, with the structure of the failure compensation controller (34), the boundedness of $\nu_0(t)$ is ensured. Thus, all signal in the closed-loop system are bounded.

Further, the tracking measurement can be generated as

$$\begin{aligned} & r_1 \int_0^t z_1^2(\tau) d\tau + r_2 \int_0^t z_2^2(\tau) d\tau \\ &= V_2(0) - V_2(t), \quad t \in (T_{\mathcal{M}}, \infty), \end{aligned} \tag{40}$$

Since V_2 as a function of t is bounded, it has that $\int_0^\infty z_1^2(\tau)d\tau < \infty$ and $\int_0^\infty z_2^2(\tau)d\tau < \infty$. According to (21), $\dot{z}_1(t)$ is bounded, it shows that $\lim_{t\to\infty} z_1(t) = 0$, which implies that $\lim_{t\to\infty} x_1(t) - x_m(t) = 0$.

The performance of the adaptive controller can be summarized to obtain the following stability and tracking properties:

Theorem 1: The adaptive failure compensation controller (34), with the adaptive scheme (28)-(33) and (35)-(36) applied to the system (8)-(9) with actuator failures (17)-(20), guarantees that all closed-loop signals are bounded and the tracking error $e(t) = x_1(t) - x_m(t)$ satisfying $\lim_{t\to\infty} e(t) = 0$.

In this section, the adaptive failure compensation controller is designed to achieve the position tracking and deal with the two kinds of parameter variations caused by either actuator failure changes or system mode changes. To handle unknown and jumping parameters, those (from system modes) with know jumping time instants are parameterized in the controller structure and those (from actuator failures) with unknown jumping time instants are both parameterized in the controller and dealt with via the use of a piecewise Lyapunov function V_2.

4. SIMULATION STUDY

In this section, a simulation study on a high-speed train is given to demonstrate the effectiveness of the proposed failures compensation scheme. The system parameters are borrowed from a CRH type train (Dong et al. (2010)), in which 4 motors are considered.

4.1 Simulation System

The mass of the train is chosen as $M_i = M = 500$ ton. Due to the tunnel, slope and curvature which lead to the changes of the resistance coefficients in the travel, 4 modes will be considered for the healthy system (m_i, a_i, b_i, c_i, ϑ_i, and D_i are defined as equations (10) and (12)):

(i) For $t < 400$ s, the train bakes up, for which the coefficients are $a_1 = 2.25$, $b_1 = -1.9\times10^{-3}$, $c_1 = 3.2\times 10^{-4}$, $\theta_1 = 0$, $D_1 = 0$.
(ii) During $400 \le t < 800$ s, the train enters the tunnel. Then only c_2 is replaced by $c_2 = 9.2 \times 10^{-4}$, with $a_2 = a_1$, $b_2 = b_1$, $\theta_2 = \theta_1$ and $D_2 = D_1$.
(iii) At 800 s, the train exits the tunnel and travels in the slope and curvature track. For $800 \le t < 1400$ s, the coefficients are $c_3 = c_1 = 3.2 \times 10^{-4}$, $\theta_3 = 0.015$, $D_3 = 0.34$, with $a_3 = a_1$, $b_3 = b_1$.
(iv) After 1400 s, the train is in the open-air and horizontal track to slow down for fully stop. For $1400 \le t < 2000$ s, the coefficients are the same as that of the baking up, i.e., $a_4 = a_1$, $b_4 = b_1$, $c_4 = c_1$, $\theta_4 = \theta_1$ and $D_4 = D_1$.

Considering the failure modes, i.e., the failure occurs before or after the system mode switching, the following failures are chosen, with whose modes and patterns are the same as that of the signal-model case but the occurrence times are different. The failure is expressed as: F_α fails for some $\alpha \in \{1, 2, 3, 4\}$,

$$F_\alpha = \begin{cases} 2 \times 10^5, & \text{for } \ 600 \le t < 1000\text{s}; \\ 2 \times 10^5(1 + \sin(0.05t - 30)), & \text{for } \ 1000 \le t < 1200\text{s}; \\ 0, & \text{for } \ 1200 \le t \le 2000\text{s}; \end{cases}$$

$F_\beta = \nu_\beta$, $\beta \ne \alpha$, $\beta \in \{1, 2, 3, 4\}$.

4.2 Simulation Results

The initial conditions are chosen as $x_d(0) = x(0) = [0 \ \ 0]^T$, and the values of the initial parameter estimates are 95% of their ideal values. Fig. 1 shows the distances including the plant distance (solid) and the desired distance (dashed). Fig. 2 shows the tracking error. From the simulation results, it can be seen that the proposed adaptive controller can achieve the close-loop stability and asymptotic tracking properties of the train even in the presence of parameters changes.

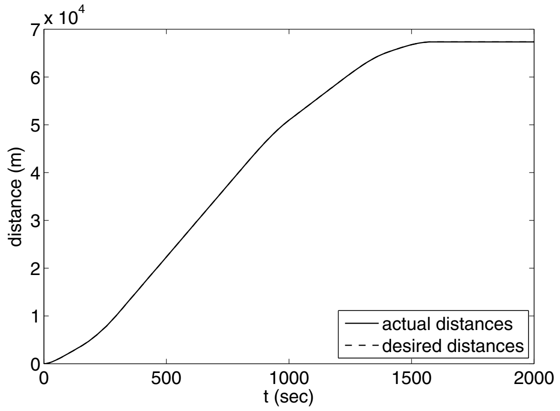

Fig. 1. Distances tracking trajectories.

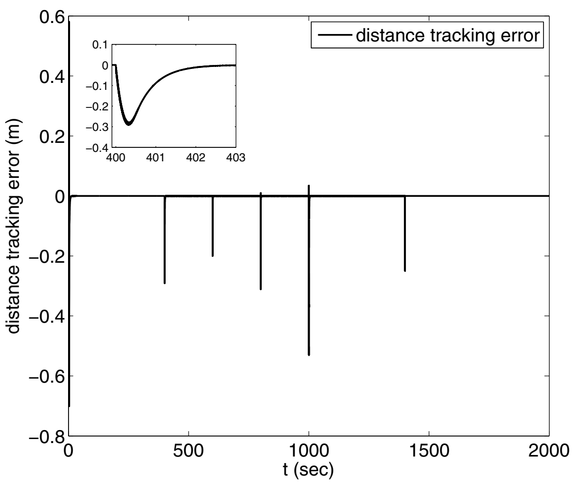

Fig. 2. Distances tracking error.

5. CONCLUSION

In this paper, the adaptive failure compensation problem is addressed for high-speed trains with traction system actuator failures, which are uncertain in time instants, values, and patterns. A new piecewise constant model with unknown parameters is introduced to represent the motion dynamics with variable parameters. An adaptive failure compensation is developed to deal with the unknown parameters in the plant and traction system actuator failures. Simulation results further confirm the obtained theoretical results.

REFERENCES

H. Dong, B. Ning, B. Cai, Z. Hou. Automatic train control system development and simulation for high-speed railways, *IEEE Circuits and Systems Magazine*, 10(2): 6-18, 2010.

Q. Song, Y. D. Song, T. Tang, B. Ning. Computationally inexpensive tracking control of high-speed trains with traction/braking saturation, *IEEE Transactions on Intelligent Transportation Systems*, 12(4): 1116-1125, 2011.

L. J. Zhang, X. T. Zhuan. Optimal operation of heavy-haul trains equipped with electronically controlled pneumatic brake systems using model predictive control methodology, *IEEE Transactions on Control Systems Technology*, 22(1): 13-22, 2014.

J. Guzinski, M. Diguet, Z. Krzeminski, A. Lewicki, H. Abu-Rub. Application of speed and load torque observers in high-speed train drive for diagnostic purposes, *IEEE Transactions on Industrial Electronics*, 56(1): 248-256, 2009.

Q. Song, Y. D. Song. Data-based fault-tolerant control of high-speed trains with traction/braking notch nonlinearities and actuator failures, *IEEE Transactions on Neural Networks*, 22(12): 2250-2261, 2011.

Y. Wang, Y. D. Song, H. Gao, F. L. Lewis. Distributed fault-tolerant control of virtually and physically interconnected systems with application to high-speed trains under traction/braking failures, *IEEE Transactions on Intelligent Transportation Systems*, 17(2): 535-545, 2016.

M. Blanke, M. Kinnaert, J. Lunze, M. Staroswiecki. *Diagnosis and fault-tolerant control*, Springer Verlag, Berlin, Heidelberg, 2003.

Q. K. Shen, B. Jiang, P. Shi, C. Lim. Novel neural networks-based fault tolerant control scheme with fault alarm, *IEEE Transactions on Cybernetics*, 44(11): 2190-2201, 2014.

G. Tao, S. M. Joshi, X. L. Ma. Adaptive state feedback and tracking control of systems with actuator failures, *IEEE Transaction on Automatica Control*, 46(1): 78-95, 2001.

G. Tao, S. H. Chen, S. M. Joshi. An adaptive actuator failure compensation controller using output feedback, *IEEE Transaction on Automatica Control*, 47(3): 506-511, 2002.

X. Zhuan, X. Xia. Optimal scheduling and control of heavy haul trains equipped with electronically controlled pneumatic braking systems, *IEEE Transactions on Control Systems Technology*, 15(6): 1159-1166, 2007.

AREMA. *Manual for Railway Engineering*, American, 1999.

V. K. Garg. *Dynamics of railway vehicle systems*, Academic Press, 1984.

Z. H. Mao, G. Tao, B. Jiang, X. Yan. Adaptive compensation of traction system actuator failures for high-speed trains, *IEEE Transactions on Intelligent Transportation Systems*, DOI:10.1109/TITS.2017.2666428, 2017.