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Research article

Robust fault detection for the dynamics of high-speed train with multi-source finite frequency interference

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ABSTRACT

This paper proposes a composite fault detection scheme for the dynamics of high-speed train (HST), using an unknown input observer-like (UIO-like) fault detection filter, in the presence of wind gust and operating noises which are modeled as disturbance generated by exogenous system and unknown multi-source disturbance within finite frequency domain. Using system input and system output measurements, the fault detection filter is designed to generate the needed residual signals. In order to decouple disturbance from residual signals without truncating the influence of faults, this paper proposes a method to partition the disturbance into two parts. One subset of the disturbance does not appear in residual dynamics, and the influence of the other subset is constrained by H_∞ performance index in a finite frequency domain. A set of detection subspaces are defined, and every different fault is assigned to its own detection subspace to guarantee the residual signals are diagonally affected promptly by the faults. Simulations are conducted to demonstrate the effectiveness and merits of the proposed method.

1. Introduction

As a fast and eco-friendly transportation system with high loading capacity, HST is gaining increasing population recent years. Safety and reliability are two crucial factors that have to be taken account of in operating and maintaining such massive railway transportation system. Therefore, different control methods have been developed for the dynamics of HST [1–3]. Due to the harsh environment with various uncertainties, where HST runs with high speed for a long time, some of the actuators and/or sensors, or plant of the HST may unavoidably be faulty, even worse failure, which may cause severe change of the system behavior. If cannot be detected in time and handled effectively, a small fault may lead to disastrous consequences causing huge casualties and inestimable economic losses finally. Advanced fault diagnosis technique is a key technology for enhancing safe and reliable operation of HST, which calls for advanced fault handling methods including fault tolerant control and fault detection to improve the safety and reliability of HST [2–8].

Fault detection of railway system has been investigated for several years, and some results can be found in literature [4–10]. Most of the early works have been focused on the structure components of the train control system so that complicated exogenous disturbance can be ignored, and some classic analysis methods of control theory are normally utilized in fault detection filter design [4–7]. Speed and load torque observers are designed to detect sensor faults for a rail vehicle motor used in HST [4].

And a case-based reasoning system is presented to detect locomotive faults [5]. In Ref. [6], aiming at the faults that may occur in the brake system, a multi-agent based diagnosis system is proposed. The ensemble mode decomposition and wavelet neural network are combined to propose an automated fault diagnosis method for the locomotive roller bearings in Ref. [7]. To identify the incident fault of high-speed railway traction, sliding-mode observer combined with the ToMFIR-based threshold are designed [8]. In Refs. [9,10], fault detection for high-speed rail vehicle suspension systems with uncertain track regularity are researched, where fault detection of actuator faults [10] and sensor faults [9] are conducted respectively. The early studies are mainly focused on the structure components of the train control system, very few researchers study the fault detection problems based on the whole train control system. And few papers take

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the situation that disturbance may be coupled with the fault signals into account, which may result in very conservative result and high miss alarm rate and false alarm rate. To sum up, fault detection of the railway system, especially when there exists multi-source disturbance in the railway system is still a challenging problem which has not yet been solved perfectly. Thus, one motivation of this paper is trying to solve the fault detection problem of the dynamics of HST with multi-source disturbance. Note that most of the existing fault detection techniques are focused on single type of faults, few of them consider different types of faults together in the fault detection process, which is inconsistent with the reality. So, another motivation of this paper is trying to propose a fault detection scheme that can deal with different types of faults for the dynamics of HST simultaneously.

So far, aiming at rapid and accurate fault detection of dynamic systems, various model-based fault diagnosis approaches including parity space-based approach [11], state estimation approach [12,13], H_∞ optimization approach [14–18], geometric approach [19–26] have been widely used. Therein, geometric approach is one of the most popular fault diagnosis methods used today. The idea of geometric approach is first introduced by Beard [19] and Jones [20] in the early seventies, and they find that the filter residual signals can have directional characteristic that can be easily associated with different faults by choosing proper feedback gain. The geometric approach is enhanced in the last decades [21–26], among them the eigenstructure assignment method has special advantages because the dynamic behavior of a linear multi-variable system can be guaranteed together with the directional characteristic of the residual, simultaneously. The main and most appealing feature of the geometric approaches is that the number of the fault detection filters needed for identifying specific numbers of faults is the least compared with other approaches. However, the geometric approaches cannot decouple the disturbance effectively, which may cause some false or miss alarms. The lack of robustness obstructs the application of the geometric approach. In order to decouple exogenous disturbance from residual dynamics, the UIO-based fault detection scheme is proposed and developed in Refs. [13,27–29]. The basic idea of combining the disturbance decoupling mechanism of UIO with the directional residual characteristic of geometric approach together is first proposed in Ref. [27]. A series of UIO-based fault detection filters are designed to isolate different faults, where the H_-/H_∞ indexes are used to make a trade-off between the sensitivity to fault signals and the robustness to disturbance [28]. While in Refs. [13,29], UIO-based fault detection filter for high-order multi-agent systems with disturbance is designed. Aiming at the case that the disturbance cannot be decoupled from residual signals completely, the H_∞ norm of the transfer function is adopted to attenuate the influence of disturbance. But, in the case that the disturbance is coupled with the fault signals, the influence of fault signals is attenuated simultaneously. By exploiting the unknown input decoupling scheme, the exogenous disturbance can be decoupled from the residual signals and the robustness can be guaranteed. However, the original approach and its following work don't take the case that disturbance may be coupled with fault signals into account, in which case the fault signals may be truncated by the unknown input decoupling scheme and attenuated by the H_∞ norm together.

This paper is focused on the composite faults detection for the dynamics of HST with multi-source disturbance. A fault detection filter is proposed, where the system states and exogenous disturbance (wind gust) are estimated together to generate residual signals. To attenuate the influence of unknown multi-source disturbance without truncating the fault signals, the unknown multi-source disturbance is partitioned into two parts. One subset of the disturbance doesn't appear in residual dynamics, and the influence of the other subset is constrained by H_∞ index in a finite frequency domain. The basic idea of this paper can be summarized as follow. The design freedom of the fault detection filter is partitioned into three parts. One part of the design freedom is used to decouple the disturbance that is not coupled with fault signals from residual completely; The other part of the design freedom is exploited to assign every different fault to its own associated detection subspace; The last part of the design freedom is used to attenuate the effect of the remaining disturbance in a finite frequency domain without truncating the influence of fault signal based on frequency discrepancies between fault signals and disturbance. The main contributions of this paper are concluded as follows:

1) The wind gust disturbance and other process disturbances generated by curve resistance, slop resistance, tunnel resistance, modeling errors, etc., which can affect the fault detection result and cannot be ignored for the dynamics of HST are considered together with three types of faults (actuator fault, sensor fault, plant fault). To attenuate the effect of wind gust disturbance, an augmented state is introduced to transform the original system to an augmented system with multi-source disturbance within finite frequency domain.
2) An approach is proposed to partition the disturbance into two parts, one subset of the multi-source disturbance is decoupled from the residual signals completely, the other subset of the multi-source disturbance is constrained by finite frequency H_∞ index. Such that the effect of multi-source disturbance can be attenuated without truncating the effect of fault signals.
3) An fault detection filter is designed in which composite faults (actuator fault, sensor fault, plant fault) are considered simultaneously. And the residual signals are diagonally affected promptly by different faults.

The remainder of this paper is organized as follows. In Section 2, the fault detection problem of the dynamics of HST with multi-source interference is formulated. We then discuss the design process of the fault detection filter in Section 3. Section 4 presents simulation results to illustrate the effectiveness and merits of the proposed fault detection filter. A brief conclusion is drawn in Section 5. The Proof of some important results proposed in this paper are given in Appendices.

Notation: In this paper, the notations are standard. Let $\mathbb{R}^n$ denotes n dimensional Euclidean space. For a matrix P, P^T, P^{-1} and P^* denote its transpose, inverse and conjugate, respectively; $He(P) := P + P^T$, P^+ denotes the Moore-Penrose pseudo inverse. Also, I_m denotes the $m \times m$ identity matrix, $0_{m\times n} \in \mathbb{R}^{m\times n}$ denotes zero block matrix, and $\otimes$ denotes the Kronecker product of matrices. For a symmetric A, by $A > 0 (\geqslant 0)$ we mean that A is positive definite (positive semidefinite). In symmetric block matrix, terms induced by symmetry are represented by $*$, diag$\{\cdots\}$ stands for block diagonal matrix.

2. Problem formulation

2.1. Force model of HST

Considering the dynamics of HST and taking the rolling mechanical resistance, aerodynamic drag and wind gust into account, the dynamics of HST can be reduced to a multi-particle model as shown in Fig. 1. In this figure, m_i, v_i, x_i denote the mass of i car, the speed of i car, and the relative distance between $i+1$ car and i car, respectively. The effort, rolling resistance and aerodynamic drag of i car are represented as u_i, $R_{m,i}$ and $R_{a,i}$.

The major resistances experienced by HST are rolling resistance and aerodynamic drag. The rolling resistance is experienced by each car of HST and the aerodynamic drag includes form drag and skin friction drag. The form drag is generated from the pressure distribution along the nose and the tail of the train, while the skin friction drag is generated over the entire surfaces of the train. As the train speed increases, the aerodynamic drag will become the major part of