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Robust sampled-data cruise control scheduling of high speed train

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ABSTRACT

This paper investigates the robust cruise control scheduling of high speed train based on sampled-data. The dynamics model of a high speed train is modeled by a cascade of cars which are connected by flexible couplers, and is subject to rolling mechanical resistance, aerodynamic drag and wind gust. The robust cruise controller is designed for high speed train based on sampled-data. By using the method of converting the sampling period into a bounded time-varying delay, the addressed problem is transformed to the problem of stability analysis of time-varying delays system. Based on Lyapunov stability theory, sufficient conditions for the existence of robust sampled-data cruise control scheduling are given in terms of linear matrix inequality (LMI), under which the high speed train can track the desired speed, the relative spring displacement between the two neighbouring cars is robustly stable at the equilibrium state, and a prescribed H_∞ disturbance attenuation level with respect to the wind gust is guaranteed, which ensures the safety and comfort of the operating of high speed train. Numerical examples are given to illustrate the effectiveness of the proposed methods.

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1. Introduction

High speed train is a type of rail transport that operates significantly faster and more eco-friendly than traditional rail traffic by using automatic train control (ATC) system. To ensure the safety and comfort of the operating of high speed train, automatic train control theory has been an important research topic and many advanced control methods are proposed to monitor and control the trains (Howlett, 1996; Yang and Sun, 1999; Khmelnitsky, 2000; Dong et al., 2010, 2013; Zhuan and Xia, 2010; Ciccarelli et al., 2012). In the existing methods for automatic train control, some researchers treated the whole train that consists of multiple cars as a single point mass and approximately characterized its motion by a single-point-mass Newton equation (Howlett, 1996; Khmelnitsky, 2000; Liu and Golovitcher, 2003). However, this model neglects the couplers that connect adjacent cars and the interactive forces among the connected cars, which will lead to an unstable motion of multi-cars train.

By considering the interactive forces among the connected cars of the train, the model treating high speed train as a cascade of masses connected by flexible couplers was proposed in Yang and Sun (1999), which can better match the reality to describe the motion of high speed train. Based on this model, the cruise control design of high speed train was intensively studied. A high-speed train was modeled as a cascade of mass connected by couplers in Yang and Sun (2001), and a mixed H_2/H_∞ cruise controller was synthesized by linear matrix inequalities to satisfy a mixed design objective of speed command

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tracking (measured by H_2 norm) and gust attenuation (measured by H_∞ norm). Using the same model, the different input/output decoupling problems for a nonlinear model of high speed train were studied in Astolfi and Menini (2002). Zhuan and Xia (2006) introduced an optimal open-loop cruise control of heavy haul trains, in which both the fuel consumptions and the in-train forces were minimized. Chou and Xia (2007) proposed a closed-loop cruise controller to minimize the running cost of heavy-haul trains equipped with electronically controlled pneumatic brake systems. An output regulation with measurement feedback for the control of heavy haul trains was studied in Zhuan and Xia (2008), which can regulate all cars' speeds to a prescribed speed profile. In Song and Song (2011), the position and velocity tracking control problems of high speed train with multiple vehicles connected through couplers were studied, and neuroadaptive fault-tolerant control algorithms were developed. Song et al. (2011) derived a multiple point mass model that reflects resistive and transient impacts of high speed train, and designed robust adaptive control with optimal task distribution for speed and position tracking under traction/braking nonlinearities and saturation limitations.

The existing methods of automatic train control are mainly confined to the continuous-time control design for continuous-time models. Because of the application of digital sensors and controllers, the sampled-data control method, for which the control signals are constant during the sampling period and change only at the sampling instant, has been more important and practical than the continuous-time control approach (Fridman et al., 2004; Gao et al., 2010; Wen et al., 2013). However, little literature can be found to deal with the sampled-data control problem for the automatic train control (ATC) system. Motivated by the above discussions, in this paper, we will consider the high speed train modeled by a cascade of cars that are connected with flexible couplers, and design the robust cruise control scheduling of high speed train based on sampled-data. Consider that the discontinuous control signals of the sampled-data control have stepwise form, which cause big trouble to analyze the system. To address this problem, the linear matrix inequality (LMI) technique can be effectively applied to analyze the system and obtain the sampled-data control gain and sampling period of the sampled-data cruise controller of high speed train. By using the method of converting the sampling period into a bounded time-varying delay, the addressed problem is transformed to the problem of stability analysis of time-varying delays system. Based on Lyapunov stability theory and LMI technique, sufficient condition for the existence of sampled-data cruise control scheduling is given in terms of LMI, which ensures that the high speed train tracks the desired speed, and the relative spring displacement between the two neighbouring cars is stabilized to the equilibrium state. Additionally, the running train will inevitably suffer from the uncertain wind gust disturbance, which seriously affect the stability as well as riding quality of the train. The robust H_∞ control method can not only guarantee the high speed train tracking the desired speed, but also ensure a small prescribed H_∞ disturbance attenuation level with respect to uncertain wind gust disturbance (Yang and Sun, 2001). Then based on the robust H_∞ control method, we design the robust cruise control scheduling of high speed train based on sampled-data, under which the high speed train can track the desired speed, the relative spring displacement between the two neighbouring cars is robustly stable at the equilibrium state, and a small prescribed H_∞ disturbance attenuation level with respect to uncertain wind gust disturbances can be guaranteed. Numerical examples are given to illustrate the effectiveness of the proposed methods. From the numerical examples, we can observe that the proposed control methods can be effectively used to track the desired speed for high speed train by considering the interactive forces among the connected cars. Moreover, the proposed robust control method effectively suppresses the uncertain wind gust disturbance to the stability of the running motion of high speed train, which ensures the safety and comfort of the operating of high speed train.

The rest of this paper is organized as follows. In Section 2, the cruise control problem of a high speed train modeled by a cascade of cars that are connected with flexible couplers is presented. In Section 3, the robust cruise control scheduling of high speed train based on sampled-data is designed. In Section 4, numerical examples are provided to demonstrate the effectiveness of the proposed methods. We conclude this paper in Section 5.

2. The dynamic model of high speed train

Let us consider the dynamics of a high speed train that are modeled by a cascade of cars connected with flexible couplers and are subject to rolling mechanical resistance, aerodynamic drag and wind gust. The force diagram of high speed train is shown in Fig. 1.

For the running motion of high speed train, couplers play an important role in the connected cars and transmit traction/braking force in the longitudinal direction. The behavior of couplers can be described by a spring model, in which the restoring force of a coupler is a function of the relative spring displacement ε between two connected cars. When $\varepsilon > 0$, it means that the spring is stretched, and the traction force is generated. Otherwise, the spring is compressed, and the braking force is generated. Here we assume that the restoring force is a linear function of the relative displacement, which is presented as follows

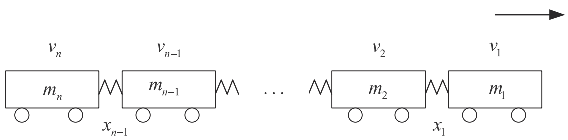

Fig. 1. Force diagram of high speed train.

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