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Research Article

Robust adaptive cruise control of high speed trains

Mohammadreza Faieghi [a,*], Aliakbar Jalali [b], Seyed Kamal-e-ddin Mousavi Mashhadi [b]

[a] Department of Electrical Engineering, Miyaneh Branch, Islamic Azad University, Miyaneh, Iran
[b] School of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran

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ABSTRACT

The cruise control problem of high speed trains in the presence of unknown parameters and external disturbances is considered. In particular a Lyapunov-based robust adaptive controller is presented to achieve asymptotic tracking and disturbance rejection. The system under consideration is nonlinear, MIMO and non-minimum phase. To deal with the limitations arising from the unstable zero-dynamics we do an output redefinition such that the zero-dynamics with respect to new outputs becomes stable. Rigorous stability analyses are presented which establish the boundedness of all the internal states and simultaneously asymptotic stability of the tracking error dynamics. The results are presented for two common configurations of high speed trains, i.e. the DD and PPD designs, based on the multi-body model and are verified by several numerical simulations.

1. Introduction

High speed train offers efficient mobility, green transportation and cost-effective travelling which is known as a feasible alternative to the aeroplanes for trips under about 650 km. One of the demanding control problems associated with HSTs is cruise control problem, that is, automatically controlling the train speed to follow a desired trajectory. The driving forces behind the increasing use of automatic control in transportation systems and the interest in the development of unmanned vehicles require modern train control systems to apply new technologies for cruise control in order to achieve high-precise velocity tracking [1,2].

The methods proposed for cruise control of HST are developed based on a motion model obtained from Newton's law which can be classified into two categories. In the first one, which mostly refers to earlier papers, the train consisting of multiple cars is considered as a single rigid body and its longitudinal motion is characterized approximately by a single-point mass Newton equation. Therefore the dynamics within the train is ignored; see for example [3–6]. In the second category a more effective model is considered. As the couplers between two adjacent cars are not perfectly rigid, the impacts from the connected cars are taken into account and a multi-body model is obtained; see for example [7–10].

In this paper we consider the multi-body model of train since it provides more accuracy in characterizing the dynamics of train. This model is a nonlinear multi-input multi-output (MIMO) representation of the train longitudinal motion and requires more complicated stability analysis and design procedure. In addition, defining the cars' velocities as the system outputs yields an unstable zero-dynamics rendering the system is non-minimum phase which challenges the controller design. In the previous papers linear or simplified nonlinear models are used to design the controller and thus, dealing with such a complexity is avoided. For example, in [7] the nonlinear model is linearized around an operating point and a mixed H_2/H_∞ controller is developed. Similarly, in [8] a linearized model is considered and a decoupling controller is proposed. Application of nonlinear methods is also studied in [9,10]. In these two papers the cars' positions are considered as the outputs. Thus, there exists no internal dynamics; the system becomes minimum-phase and position tracking is obtained instead of velocity tracking. In addition, the nonlinear model that has been utilized is a simplified version of the multi-body model. More specifically, a second-order differential equation is derived in terms of the first car's position which just partially describes the train motion. This simplified model is rather simple in describing the details of train dynamics. To the authors' best knowledge, cruise control design for HST is not addressed yet by using the nonlinear MIMO model, i.e. the original multi-body model and the stability of internal dynamics is not studied as well.

Contemporary HST designs fall into different categories according to the composition of traction forces. Two important types are Push Pull Driving (PPD) design and Distributed Driving (DD) design. The PPD type has only two motorized cars located at both ends of a train, and the trailers are between the motorized cars.

* Corresponding author.
E-mail address: mfaieghi@gmail.com (M. Faieghi).

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For the DD type every car has its own motor. In [7] a comparative study is provided between these two kinds of designs and it is revealed that the DD trains are superior in terms of velocity tracking and disturbance rejection. However, the PPD trains have the advantage of energy saving and low maintenance cost. Velocity tracking problem of PPD trains is more complicated in comparison with the DD trains since it has a larger internal dynamics and one has to show its stability to obtain a meaningful tracking.

In a realistic problem HSTs suffer from unknown parameters and external disturbances. Generally, the weight of passengers and loads vary in each travel and consequently the total weight of train will be unknown. This is a considerable source of uncertainty in the control system. Other parametric uncertainties include the mechanical resistance parameters which change according to the environmental conditions, the stiffness coefficient of couplers due to their nonlinear behavior, etc. Wind gust is a major disturbance in HST cruise control which seriously affects stability as well as riding quality. Furthermore, there may be other external disturbances such as tunnel resistance, ramp resistance, track slope, and curve resistance. These perturbations are considered in [9,10] and robust controllers are proposed for compensation of their effects.

In this paper we consider the velocity tacking problem in the presence of both parametric uncertainties and external disturbances. The proposed controller is based on adaptive control theory. By the use of adaptive controller there is no need to have a priori information about the bounds on uncertain parameters and the controller is capable of changing itself according to the existing conditions. These are the main advantages of adaptive methods in comparison with other robust techniques [11–15]. Here, to deal with unknown parameters, an adaptive controller is designed by means of Lyapunov direct method and sufficient conditions are obtained to guarantee the stability of closed-loop system. Then, in order to deal with external disturbances, we incorporate the adaptive technique with Lyapunov redesign to come up with a robust adaptive control law which is able to attenuate the effects of unknown parameters and external disturbances simultaneously. However, as the system is non-minimum phase, we need to stabilize the internal dynamics to obtain a meaningful tracking [16]. For this purpose, the output redefinition method is adopted from [17]. The main results of this paper consist of the following aspects:

- The cruise controller is developed, for the first time, based on the original multi-body nonlinear MIMO model.
- The stability of internal dynamics is proven for different train configurations and a theoretical justification is provided for stability of all the trailers. Such results are not presented in none of the previous papers [7–10].
- Parametric uncertainties and external disturbances are considered simultaneously and sufficient conditions are given for asymptotic tracking in the presence of such perturbations.

The remainder part of this paper is organized as follows. We introduce the train dynamics and present the problem statement in Section 2. The output redefinition approach and stabilization of the internal dynamics are included in Section 3. The robust adaptive controller is developed in Section 4. We examine the performance of the proposed controller via numerical simulations in Section 5. An introduction to practical applicability of the proposed cruise controller is given in Section 6. Finally, our conclusions appear in Section 7.

Notation: Throughout the paper, unless otherwise mentioned, we will use x_i to denote the i-th element of the vector x. When x_i itself is a vector, its components will be denoted by x_i^j. Vectors and matrices, if not explicitly stated, are assumed to have appropriate dimensions. $\|\cdot\|_p$ is used to denote the p-norm of a vector and if the subscript is dropped, it indicates any p-norm. For a given matrix A, $\lambda_{max}(A)$ and $\lambda_{min}(A)$ denote its largest and smallest eigenvalues, respectively. The positive definiteness of A is shown by $A>0$. I_n shows an n-dimensional identity matrix. In addition, we abuse the notation 0 to denote any zero matrices.

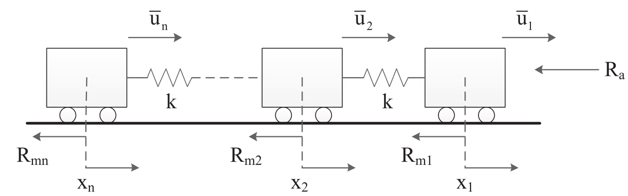

Fig. 1. Force diagram of HST.

2. Dynamics of HST

2.1. Mathematical modelling

The force diagram of HST is depicted in Fig. 1 where x_i, $\bar{u}_i$ and R_{mi} denote position, traction force and mechanical resistance of the i-th car, respectively. The aerodynamic drag is indicated by R_a. The behavior of couplers can be described approximately by a linear spring with stiffness coefficient k. Let m_i be the mass of i-th car, then R_{mi} and R_a are given by

$$R_{mi}=(c_0+c_v\dot{x}_i)m_i, \tag{1}$$

$$R_a=c_aM\dot{x}_1^2, \tag{2}$$

where c_a, c_v and c_0 are positive constants and M is the total mass of train given by $\sum_{i=1}^n m_i$. Let $\Delta x_{i,j}=x_i-x_j$, then based on Newton's equation of motion we obtain

$$\begin{cases} m_1\ddot{x}_1=-k\Delta x_{1,2}-R_{m1}-R_a+\bar{u}_1 \\ m_i\ddot{x}_i=-k(\Delta x_{i,i-1}+\Delta x_{i,i+1})-R_{mi}+\bar{u}_i, \quad i=2,\dots,n-1 \\ m_n\ddot{x}_n=-k\Delta x_{n,n-1}-R_{mn}+\bar{u}_n. \end{cases} \tag{3}$$

Notice that for the PPD design, we have $\bar{u}_i=0$, $i=2,\dots,n-1$. Let $v_i=\dot{x}_i$ be the velocity of i-th car, then (3) can be conveniently represented in the following normal form:

$$\begin{cases} \dot{x}=v, \\ \dot{v}=f(x,v,t)+g(t)\bar{u}, \end{cases} \tag{4}$$

where $x, v\in\mathcal{R}^n$ are position and velocity vectors,

$$f(x,v,t)=\begin{pmatrix} -\dfrac{k}{m_1}\Delta x_{1,2}-c_0-c_vv_1-\dfrac{c_aMv_1^2}{m_1} \\ -\dfrac{k}{m_2}(\Delta x_{2,1}+\Delta x_{2,3})-c_0-c_vv_2 \\ \vdots \\ -\dfrac{k}{m_n}\Delta x_{n,n-1}-c_0-c_vv_n \end{pmatrix}, \tag{5}$$

and

$$g(t)=(1/m_1,\dots,1/m_n)^T. \tag{6}$$

The above mathematical modelling is based on [7]. Notice that we have assumed that the couplers are linear springs which have constant stiffness coefficients; however, in practice, the stiffness coefficients depend on the displacement nonlinearly. Since such a nonlinear behavior is not simply measurable during the train operation, we consider any nonlinear deviation of stiffness coefficients as additive parametric uncertainties. In addition, we consider nonlinearities arising from track profile such as track slope as