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Balancing and suppression of oscillations of tension and cage in dual-cable mining elevators[☆]

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ABSTRACT

Dual-cable mining elevator has advantages in the transportation of heavy load to a large depth over the single cable elevator. However challenges occur when lifting a cage via two parallel compliant cables, such as tension oscillation inconformity between two cables and the cage roll, which are important physical variables relating to the fatigue fracture of mining cables. Mining elevator vibration dynamics are modeled by two pairs of 2×2 heterodirectional coupled hyperbolic PDEs on a time-varying domain and all four PDE bottom boundaries are coupled at one ODE. We design an output feedback boundary control law via backstepping to exponentially stabilize the dynamic system including the tension oscillation states, tension oscillation error states and the cage roll states. The control law is constructed with the estimated states from the observer formed by available boundary measurements. The exponential stability of the closed-loop system is proved via Lyapunov analysis. Effective suppression of tension oscillations, reduction of inconformity between tension oscillations in two cables, and balancing the cage roll under the proposed controller are verified via numerical simulation.

1. Introduction

Mining cable elevator: In mining exploitation, a cable elevator, which is used to transport the cargo and miners between the ground and the working platform underground, represents an indispensable equipment. Cable plays a vital role in the deep mining elevators because its advantages of low bending and torsional stiffness, resisting relatively large axial loads, are helpful to the heavy load and large depth transportation. However, the compliance property or stretch and contract abilities of cables, tend to cause mechanical vibrations, which lead to premature fatigue fracture due to tension oscillations. Therefore, the importance of suppressing the tension oscillations cannot be overestimated, considering the safety of personnel and profitability.

Single-cable mining cable elevator: A common arrangement in elevator systems, referred to a single-drum system (Wang, Koga, Pi, & Krstic, 2018), comprises a driving winding drum, a steel wire cable, a head sheave, and a cage. The important feature of this systems is that the cable is of a time-varying length. The vibration dynamic model is a wave PDE–ODE coupled system on a time-varying domain. Suppressing the axial vibrations distributed in the cable and attenuating a disturbance at the cage through the control force applied at the head sheave in such a single cable elevator have been achieved in Wang, Koga et al. (2018) and Wang, Tang, Pi, and Krstic (2018) respectively.

Dual-cable mining cable elevator: For the operation at a greater depth, such as over 2000 m, and carrying a heavier load, the single cable elevator is not suitable. Because a very thick cable is required to bear the heavy load and such a cable, at high bending, causes problems in the winding on the winder drum. A dual-cable mining elevator (Wang, Pi, Hu, & Gong, 2017) shown in Fig. 1 is proposed to solve this problem, where the requirement of a very thick cable can be removed because two cables tow the cage. However, the imbalance problem such as cage roll frequently appears in the dual-cable elevator, which is shown in Fig. 1 where taut cables are used as flexible guide rails (Wang, Pi et al., 2017) because traditional steel rails are with high cost of manufacture and installment in deep mines. Cage roll would increase the error of oscillation tensions between two cables, and enlarge the oscillation amplitude of the tension in cables, which accelerates premature fatigue and requires inspections and costly repairs. One feasible

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and possible arrangement to balance the cage roll and suppress the tension oscillations in cables of the dual-cable mining elevator is applying additional control forces through actuators at floating head sheaves shown in Fig. 1. However, designing control forces applied at top boundaries of the cables to balance a cage coupled with the bottom boundaries through two time-varying length compliant cables and suppress the tension oscillations in cables is a challenging task, which has heretofore remained unsolved.

Control of heterodirectional coupled hyperbolic PDE systems: Mathematically, the vibration dynamic model of a dual-cable mining elevator can be abstractly described by two pairs of 2×2 heterodirectional coupled hyperbolic PDEs on a time-varying domain and all four PDE bottom boundaries are coupled at one ODE, which is reversibly converted from the system consisting of two wave PDEs coupled with one ODE on a time-varying domain using the Riemann coordinates. We set out to exponentially stabilize such a strongly coupled and time-varying distributed parameter system in the sense of H^1 norm via the output control design at one boundary.

Some theoretical results on controlling coupled hyperbolic PDEs systems have emerged over the last decade. Backstepping boundary stabilization and state estimation of a 2×2 linear hyperbolic system were considered in Vazquez, Krstic, and Coron (2011). A full-state control law was proposed to exponentially stabilize 2×2 hyperbolic linear systems in Coron, Vazquez, Krstic, and Bastin (2013). Stabilization of 2×2 first-order hyperbolic linear PDEs with uncertain parameters was solved via adaptive control in Anfinsen and Aamo (2017a, 2018) and Yu, Vazquez, and Krstic (2017) using identifier or swapping design. Backstepping design of output feedback regulators that achieve regulation in finite time for boundary controlled linear 2×2 hyperbolic systems was presented in Deutscher (2017b). Moreover, stabilization of $n + 1$ coupled first-order hyperbolic linear PDEs was considered in Di Meglio, Vazquez, and Krstic (2013). A control problem of a first-order hyperbolic linear PDE general system where the number of PDEs in either direction is arbitrary was solved in Hu, Di Meglio, Vazquez, and Krstic (2016). Some results about control of linear hyperbolic coupled PDEs cascaded with ODEs were also presented. Output feedback control law of a 2×2 linear hyperbolic system cascaded with an ODE acting as disturbance dynamics was developed in Aamo (2013) and Anfinsen and Aamo (2015). An observer design for a class of hyperbolic PDE–ODE cascade systems with a boundary measurement was presented in Hasan, Aamo, and Krstic (2016). Controller and observer design for a $n \times m$ linear hyperbolic system cascaded with an ODE was proposed in Anfinsen and Aamo (2017b). The output regulation problem for general linear heterodirectional hyperbolic systems with spatially-varying coefficients, where disturbances described by a cascaded ODE at both boundaries, distributed in-domain or at the output to be controlled, was solved in Deutscher (2017c). The research on control of the coupled linear hyperbolic PDE systems coupled with an ODE at the non-controlled boundary is limited. In a very recent result, the state-feedback boundary control design of a 2×2 linear hyperbolic PDE–ODE coupled system with non-local terms was solved in Su, Wang, and Krstic (2018). The state-feedback stabilization of a general linear hyperbolic PDE–ODE coupled system was considered in Di Meglio, Bribiesca, Hu, and Krstic (2018), where an ODE was stabilized through compensating linear coupled hyperbolic PDEs on a fixed domain in the actuating path. An observer-based output feedback controller with anti-collocated measurements was proposed to stabilize general linear heterodirectional hyperbolic PDE–ODE systems with spatially varying coefficients in Deutscher, Gehring, and Kern (2018).

Main contribution:

(1) We suppress the tension oscillations of two cables and the cage roll in an ascending/descending mining elevator, where the two cables with in-domain viscous damping are coupled at the moving cage. It is developed from our previous work (Wang, Koga et al., 2018; Wang, Tang et al., 2018) where the vibration suppression of a single-cable ascending mining elevator neglecting the cable in-domain viscous damping is considered. The challenges arise when the in-domain viscous damping is included and both ascending/descending motions are taken into account, because the internal coupling (Roman, Bresch-Pietri, Prieur, & Sename, 2016) is introduced and the sign of the derivative of the time-varying domain affects Lyapunov stability analysis. Suppression of tension oscillations also makes the task harder than vibration suppression (Wang, Koga et al., 2018; Wang, Tang et al., 2018) because, in addition to the exponential stability result in the sense of $\|u_x(\cdot,t)\|^2+\|u_t(\cdot,t)\|^2$, the exponential stability estimate $\|u_{xx}(\cdot,t)\|^2 + \|u_{xt}(\cdot,t)\|^2$ should be produced.

(2) Suppression of tension oscillations in the dual-cable mining elevator can be mathematically described as exponential stabilization of two pairs of 2×2 heterodirectional hyperbolic systems with source terms on a time-varying domain, and all hyperbolic PDEs coupled with an ODE in the boundary anti-collocated with the control input. The related theoretical results in Anfinsen and Aamo (2017b), Anfinsen, Diagne, Aamo, and Krstic (2017) and Deutscher (2017a) only solve the problem of general coupled heterodirectional hyperbolic PDEs cascaded with ODEs on fixed domains.

(3) Different from the very recent results in Deutscher et al. (2018) and Di Meglio et al. (2018) which stabilize the general heterodirectional hyperbolic PDE–ODE coupled system on a fixed domain in L^2 sense, we stabilize a 2×2 heterodirectional hyperbolic PDE–ODE coupled system on a time-varying domain in H^1 sense.

(4) In the field of control applications, this is the first control design to suppress roll and axial vibrations of a moving object anti-collocated with the control input through two parallel compliant cables of time-varying length, whose tension oscillations are suppressed to zero simultaneously.

Organization: The rest of the paper is organized as follows. The dynamics of a dual-cable mining elevator with material damping of the steel cables is presented in Section 2. A state observer is designed and proved exponentially convergent to the plant in Section 3. An observer-based output feedback controller is designed via backstepping in Section 4. The exponential stability of the closed-loop system and the exponential convergence of the control inputs are proved in Section 5. The simulation results are provided in Section 6. The conclusion and future work are presented in Section 7.

Notation: Throughout this paper, the cable number (1,2) in the dual-cable mining elevator are denoted as the subscripts: $i = 1, 2$ or $j = 2, 1, j \neq i$. The partial derivatives and total derivatives are denoted as: $f_x(x,t) = \frac{\partial f}{\partial x}(x,t)$, $f_t(x,t) = \frac{\partial f}{\partial t}(x,t)$, $\gamma'(x) = \frac{d\gamma(x)}{dx}$, $\dot{X}(t) = \frac{dX(t)}{dt}$.

2. Problem formulation

2.1. Dynamics of dual-cable mining elevators

The actual displacement $z_i^*(x,t)$, $i = 1, 2$ of each point in the cables can be considered as the sum of the translation $l(t)$