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Research article

Output feedback boundary control of an axially moving system with input saturation constraint

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ABSTRACT

This paper is concerned with boundary control for an axially moving belt system with high acceleration/deceleration subject to the input saturation constraint. The dynamics of belt system is expressed by a nonhomogeneous hyperbolic partial differential equation coupled with an ordinary differential equation. First, state feedback boundary control is designed for the case that the boundary states of the belt system can be measured. Subsequently, output feedback boundary control is developed when some of the system states can not be accurately obtained. The well-posedness and the uniformly bounded stability of the closed-loop system are achieved through rigorous mathematical analysis. In addition, high-gain observers are utilized to estimate those unmeasurable states, the auxiliary system is introduced to eliminate the constraint effects of the input saturation, and the disturbance observer is adopted to cope with unknown boundary disturbance. Finally, the control performance of the belt system is illustrated by carrying out numerical simulations.

1. Introduction

Flexible structure systems play a significant role in a variety of applications of mechanical engineering such as marine risers [1,2], crane cables [3], aircraft wings [4], manipulators [5,6], wind turbines [7], axially moving systems [8–25] and so on. However, the excessive vibration of the flexible structures due to the distributed flexibility property and disturbance loads can degrade the product quality and limit the process productivity [3,7]. Thus, the vibration suppression of the flexible structure systems for improving performance has gained considerable interest of many researchers.

In recent years, to solve the control spillover problem generated by model reduction methods [26], which are to extract a finite-dimensional subsystem to be controlled and then to neglect the remaining infinite-dimensional dynamics in the design, many researchers have investigated the fusion of boundary control with other advanced control techniques where the control design is implemented based on the original infinite-dimensional model [27–37]. In [27,28], the authors propose boundary controls for stabilizing the flexible mooring lines and the rotating shear beam. In [29,30], the infinite-dimensional backstepping methods are adopted to stabilize an one-dimensional wave equation and the parabolic PDEs. The combination of boundary control with intelligent control for distributed parameter systems are investigated in [31,32]. In [33,34], boundary control schemes are constructed for flexible systems with input saturation and output constraint to suppress the vibration. In [35], a boundary control with disturbance adaptation is presented to attenuate the plate vibration and the controlled system is proved to be exponentially stable. In [36], a boundary control is developed to globally stabilize nonlinear elastic systems and the wellposedness of closed-loop is discussed. In [37], a hybrid Euler-Bernoulli vibrating beam is regulated by proposing the model-based control laws and the closed-loop system stability is achieved based on Lyapunov functions. For active control of axially moving systems, the great progress has been made in boundary control synthesis based on Lyapunov's direct method [10–25]. Among the literatures of boundary control for axially moving systems, it is worth noting that the control design is restricted to suppress the vibration of the system, and the input saturation constraint of the actuator is not taken into account. Despite the significant progress of boundary control for vibration suppression of axially moving systems, studies of control for the axially moving system with high acceleration/deceleration and the input saturation constraint are limited. From the point of view of practical engineering, the effects of input saturation constraint exist in almost all the systems due to the limitation of the actuators or the inherent physical constraints of the systems. Moreover, it often severely limits system performance, gives rise to undesirable inaccuracy or even leads

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instability [38]. After taking into consideration the input saturation constraint, the control scheme design will be more difficult compared to the previous works.

For the control schemes designed in literatures [10–25], the authors assume that all the system state signals can be directly measured or obtained by algorithms, but it need to be noted that some of the system signals can't be directly or accurately obtained due to the noises in practice, and then the proposed control schemes in the existing works won't be able to be implemented. Therefore, to solve those issues, high gain observers will be employed to estimate the unmeasurable states for output feedback control, which is currently lacking in the literature of boundary control for axially moving systems.

In this paper, we consider an axially moving accelerated/decelerated belt system of Surface Mount Technology equipments (SMTs) with input saturation constraint. The main objectives are to develop boundary control for ensuring the vibration reduction of the belt system and simultaneously to compensate for the input saturation effects. Comparing with the existing studies, the main contributions of this paper are highlighted as follows

(i) First, state feedback boundary control is developed to suppress the vibration of the belt system when all the boundary states can be measured. Subsequently, output feedback boundary control is proposed for the case that there are unmeasurable system states.
(ii) The auxiliary system is employed to handle the constraint effects of the input saturation and high-gain observers are adopted to estimate the unmeasurable states.
(iii) The existence and uniqueness of the solutions for the closed-loop belt system are proven based on Sobolev spaces, and the uniformly bounded stability is achieved.

The outline of this paper is structured as follows. The dynamics of the belt system and the input saturation model are given in Section 2. The state and output feedback control schemes are developed for vibration suppression of the belt system and the elimination of the input saturation effects via constructing a proper Lyapunov function candidate in Section 3, where the well-posedness and stability of the closed-loop system are demonstrated. Numerical simulations are conducted in Section 4, and the conclusion is provided in Section 5.

2. Problem formulation

As shown in Fig. 1, let $w(x,t)$ be the vibration displacement, L be the length of the controlled span, m_c be the mass of the actuator, $a(t)$ be the high acceleration/deceleration of the belt, $v(t)$ be the axial speed of the belt, and $u(t)$ be the control input exerted at the right boundary of the belt. The effect of the uncontrolled span L' is regarded as an unknown boundary disturbance $d(t)$ and the effect of the high speed motion of the mounting head is taken as an unknown distributed disturbance $f(x,t)$. Notations are defined as follows: $(\cdot)(t) = (\cdot)$, $(\cdot)(x,t) = (\cdot)$, $(\cdot)_x = \partial(\cdot)/\partial x$ and $(\cdot)_t = \partial(\cdot)/\partial t$.

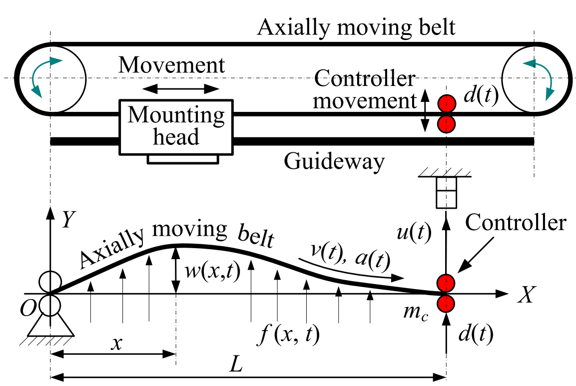

Fig. 1. Schematic of an axially moving belt system of SMT.

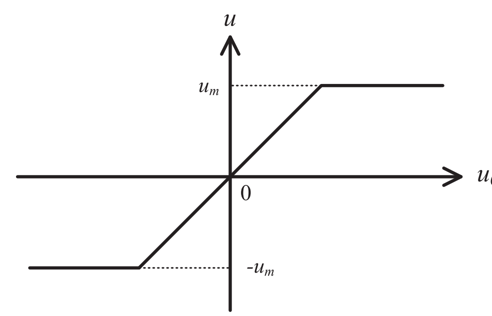

Fig. 2. Actuator input saturation model.

In this paper, we consider an axially moving accelerated/decelerated system [24], where the governing equation is given as

$$mw_{tt} + (ma + cv)w_x + 2mvw_{xt} + \left(mv^2 - T\right)w_{xx} + cw_t - f = 0 \tag{1}$$

$\forall\ (x,t) \in (0,L) \times [0,+\infty)$, and the corresponding boundary conditions are derived as

$$\begin{cases} w(0,t) = 0 \\ m_c w_{tt}(L,t) + Tw_x(L,t) + d_s w_t(L,t) - u - d = 0 \end{cases} \tag{2}$$

$\forall\ t \in [0,+\infty)$.

In this paper, we consider the axially moving accelerated/decelerated system with the input saturation constraint. As shown in Fig. 2, the input saturation model [38] is given as follows

$$u(t) = \begin{cases} \mathrm{sgn}(u_0(t))u_m, & |u_0(t)| \geq u_m \\ u_0(t), & |u_0(t)| < u_m \end{cases} \tag{3}$$

where $u_0(t)$ is the designed control command and u_m is the saturation limit.

3. Boundary control design

In this section, to achieve control objectives, boundary controls are constructed to make the presented belt converge to a small neighborhood of zero based on Lyapunov's direct method. In this paper, two cases for the presented belt system are analyzed: (i) state feedback boundary control, that is, the state signals $w(L,t)$, $w_x(L,t)$ and their first order time derivative terms $w_t(L,t)$, $w_{xt}(L,t)$ in the proposed control law are directly obtained by sensors or algorithms; (ii) output feedback boundary control, that is to say, the terms $w_t(L,t)$ and $w_{xt}(L,t)$ are obtained using high-gain observers.

3.1. Preliminaries

Relevant lemmas and assumption for the subsequent studies are presented in the following.

Lemma 1. *Let* $\kappa_1(x,t), \kappa_2(x,t) \in \mathbb{R}$, $\nu > 0$ *with* $(x,t) \in [0,L] \times [0,+\infty)$, *the following property holds [39]*

$$|\kappa_1\kappa_2| = \left|\left(\frac{1}{\sqrt{\nu}}\kappa_1\right)\left(\sqrt{\nu}\kappa_2\right)\right| \leq \frac{1}{\nu}\kappa_1^2 + \nu\kappa_2^2 \tag{4}$$

Lemma 2. *Let* $\kappa(x,t) \in \mathbb{R}$ *be a function defined on* $(x,t) \in [0,L] \times [0,+\infty)$ *satisfying the boundary condition* $\kappa(0,t) = 0$, *then the following property holds [39]*