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# Stabilization of an axially moving accelerated/decelerated system via an adaptive boundary control

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ABSTRACT

In this study, an adaptive boundary control is developed for vibration suppression of an axially moving accelerated/decelerated belt system. The dynamic model of the belt system is represented by partial-ordinary differential equations with consideration of the high acceleration/deceleration and unknown distributed disturbance. By utilizing adaptive technique and Lyapunov-based back stepping method, an adaptive boundary control is proposed for vibration suppression of the belt system, a disturbance observer is introduced to attenuate the effects of unknown boundary disturbance, the adaptive law is developed to handle parametric uncertainties and the S-curve acceleration/deceleration method is adopted to plan the belt's speed. With the proposed control scheme, the well-posedness and stability of the closed-loop system are mathematically demonstrated. Simulations are displayed to illustrate the effectiveness of the proposed control.



## 1. Introduction

The flexible structures such as beams, risers, belts, strings and others have been widely applied in many mechanical areas [1,2]. These structures will exhibit mechanical vibration when the payloads or disturbances are loaded. However, the undesired and excessive vibrations become one of the main quality-limiting and productivity-limiting factors, especially in high-speed precision machine systems. In recent years, the rapid developments of the control and information techniques make it possible to develop complex electromechanical control systems for vibration suppression of flexible structures.

The control scheme design for vibration suppression of flexible structures is a challenging task. Firstly, the flexible structure system modeled by a partial differential equation (PDE) and a set of ordinary differential equations (ODEs) is difficult to control due to the infinite-dimensionality of the system [3]. The conventional control methods for PDE are based on truncated finite-dimensional model of the system by neglecting high-frequency modes, which would result in some problems such as high-order controller, spillover instability, etc. [4–6]. Secondly, the dynamic model of flexible structure may contain unknown parametric and disturbance uncertainties, which would make the model-based control design methods unfeasible [7]. To solve these problems, some researchers have integrated boundary control with other advanced control techniques such as PID control [8,9], robust and adaptive control [10–13], learning control [14], backstepping control [15–21], etc., to design vibration control schemes for the infinite-dimensional system.

For active vibration control of axially moving systems, the boundary control synthesis which is designed based on the infinite-dimensional model has also made significant progress. The vibration control strategies for axially moving beams are presented in [22,23], for axially moving strings are presented in [24–26] and for axially moving belts are presented in [27,28]. Among these works, many advanced control techniques are employed to design boundary control laws for vibration suppression of axially moving systems. It is notable that these existing studies about axially moving systems were limited either to cases with constant axial speed or to time-varying axial speed, and moreover they were also researched without consideration of unknown distributed disturbance (UDD). However, in practice, most of axially moving systems are worked with not only varying speed but also high acceleration/deceleration (H-A/D) for efficiency improvement under both UDD and boundary disturbance, especially in high-speed precision machine systems. Hence, the first novelty of this paper is the consideration of the dynamics of the H-A/D and UDD, and then the axially moving system will be governed by a nonhomogeneous PDE, which makes the system

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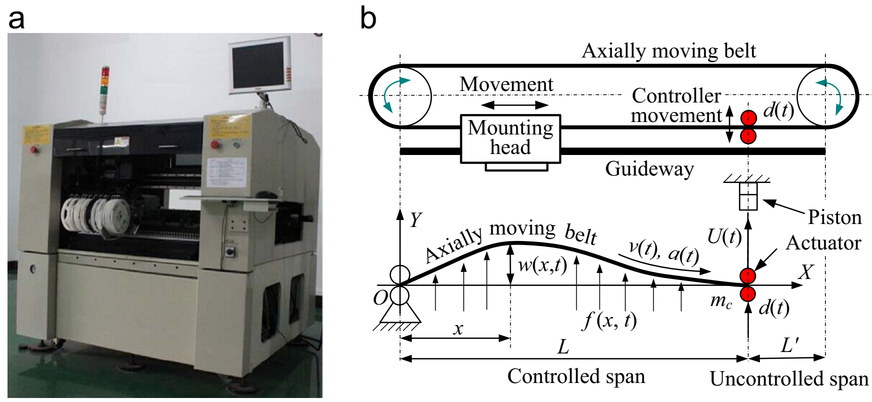


**Fig. 1.** An axially moving belt system of SMT: (a) SMT. (b) Schematic.

model and vibration control strategy design quite different with the existing works.

Meanwhile, in Refs. [15–21], many successful applications of the boundary control integrated with backstepping method/technique have been displayed to nonaxially moving (stationary) systems such as beams, waves and others, while the successful application of this control method to axially moving systems with both parametric and disturbance uncertainties has not yet been reported elsewhere. In addition, the boundary control synthesis design for axially moving systems is more difficult than that for stationary systems due to the existence of the H-A/D, UDD and system uncertainties. Thus, the second novelty of this paper is the design of an adaptive boundary control by using Lyapunov-based backstepping method to suppress the vibration of the presented belt system and compensate for both the parametric and disturbance uncertainties.

Fig. 1 shows a kind of Surface Mount Technology equipment (SMT) which is researched and developed by our team. Its axially moving belt system, see Fig. 1(b), is divided into a controlled span and an uncontrolled span by an input actuator. This belt system is worked with H-A/D and subjected to both UDD $f(x,t)$ and boundary disturbance $d(t)$, where $f(x,t)$ is arisen from the Mounting head and $d(t)$ is arisen from the uncontrolled span. The S-curve acceleration/deceleration (Sc-A/D) method, which is able to provide soft starting and stopping motion by gently increasing the acceleration and deceleration, can overcome the weaknesses of the traditional linear or exponential acceleration/deceleration control methods such as shock and mutation [29], so it is widely adopted in high-speed precision systems. Hence, the third novelty of this paper is the adoption of the Sc-A/D method to plan the axial speed of the presented belt system.

In this paper, our interest lies in the utilization of the Lyapunov-based backstepping method to develop an adaptive boundary control for vibration suppression of an axially moving accelerated/decelerated belt system where there are both parametric and disturbance uncertainties. The dynamics of the H-A/D and UDD are calculated into the model of the presented belt system. An adaptive boundary control with disturbance observer is developed by utilizing adaptive technique, Sc-A/D and Lyapunov-based backstepping methods to suppress the vibration of the belt's controlled span, compensate for the system parametric uncertainties and attenuate the boundary disturbance effects. The existence, uniqueness and convergence of the solution of the closed-loop system are proved based on Sobolev spaces.

The rest of this paper is organized as follows. The governing equation and boundary conditions of the presented belt system are obtained in Section 2. An adaptive boundary control with disturbance observer is proposed and the well-posed problems of the closed-loop system are discussed in Section 3. Simulations are presented to verify the validity of the proposed control scheme in Section 4 and the conclusions are given in Section 5.

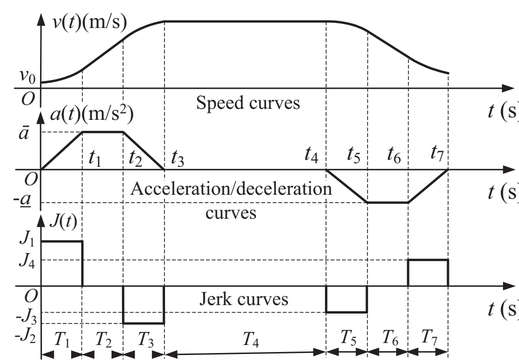


**Fig. 2.** A typical Sc-A/D process.

## 2. System model

In this section, the mathematical model of the presented belt system including the dynamics of the Sc-A/D and UDD is derived by utilizing the extended Hamilton's principle.

### 2.1. Principle of Sc-A/D

Fig. 2 shows a typical Sc-A/D process, which is divided into seven segments by time instants $t_1$–$t_7$. Let $v(t)$ be the axial speed of the belt, $v(t)>0$ for all $t$, $v_0$ be the initial axial speed, $a(t)$ be the H-A/D of the belt, $\bar{a}>0$ and $\underline{a}>0$ be the maximum acceleration and maximum deceleration respectively, the jerks $J_1 \sim J_4$ be the time derivatives of $a(t)$ respectively. Then $a(t)$ is calculated as

$$a(t)=\begin{cases} J_1 t, & 0 \le t < t_1 \\ \bar{a}, & t_1 \le t < t_2 \\ \bar{a}-J_2(t-t_2), & t_2 \le t < t_3 \\ 0, & t_3 \le t < t_4 \\ -J_3(t-t_4), & t_4 \le t < t_5 \\ -\underline{a}, & t_5 \le t < t_6 \\ -\underline{a}+J_4(t-t_6), & t_6 \le t < t_7 \end{cases} \tag{1}$$

Let $T_i=t_i-t_{i-1}, i=1,2,3,4,5,6,7$ and $t_0=0$, then $v(t)$ is obtained