Neurocomputing 000 (2017) 1–7

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Neural network based boundary control of a vibrating string system with input deadzone

Zhijia Zhao [a], Xiaogang Wang [a], Chunliang Zhang [a], Zhijie Liu [b,*], Jingfeng Yang [c,**]

[a] School of Mechanical and Electrical Engineering, Guangzhou University, Guangzhou 510006, China
[b] School of Automation Science and Electrical Engineering, Beihang University, Beijing 100083, China
[c] Open Laboratory of Geo-spatial Information Technology and Application of Guangdong Province, Guangzhou Institute of Geography, Guangzhou 510070, China

ARTICLE INFO

Article history:
Received 7 July 2017
Revised 12 September 2017
Accepted 15 September 2017
Available online xxx

Communicated by Hui Zhang

Keywords:
Distributed parameter systems
Input deadzone
Vibration control
Neural network
Disturbance observer

ABSTRACT

In this paper, a boundary control scheme is developed for a vibrating flexible string system subject to input deadzone and external disturbance. First, a basic boundary control scheme is proposed to suppress the string's vibration based on the backstepping method. Subsequently, a radial basis function neural network (RBFNN) is utilized to handle the effect of the input deadzone and a disturbance observer is exploited to track the external disturbance. Under the proposed control, the uniformly ultimately bounded stability of the closed loop system is achieved through rigorous Lyapunov analysis without any discretization or simplification of the dynamics in the time and space. Finally, simulation results are demonstrated for control performance verification.

1. Introduction

Recently, string-type structure has been one of the most popular flexible mechanical structures applied in engineering community due to the advantages of light weight, low energy consumption and good flexibility [1–4]. However, the excess vibrations of the structure will lead to performance degradation, which limits the broad application in industrial engineering. Motivated by the vibration challenge, great concern of both mechanical and control engineers has been provoked in recent decades.

For the sake of dynamical analysis, the string-type structure is deemed as a distributed parameter system (DPS) with infinite dimensional feature, which is expressed by hybrid partial-ordinary differential equation (PDE-ODE) in mathematical sense. Control for DPS mainly contains model reduction approach and boundary control. Model reduction approach is to be implemented based on the extraction of a finite-dimensional subsystem to be controlled and then the neglect of the remaining infinite-dimensional dynamics in the design [5–8], which will give rise to control spillover. Boundary control can resolve the above issue and the control scheme design is based on infinite dimensional system dynamics, which is generally considered to be physically more realistic due to nonintrusive actuation and sensing [9–14]. In recent years, the boundary control design for flexible string-type systems to increase performance have obtained an even more great development [15–22]. To mention a few, in [15], the state feedback and output feedback control strategies are introduced to globally stabilize an axial belt system and Lyapunov-based analysis is employed to ensure the stability of the controlled system. In [16], the fusion of boundary control with robust adaptive control is presented to control the vibration of a class of axially moving accelerated/decelerated system, where the stability of the controlled system is demonstrated by using Lyapunov's synthetic method. In [17], the vibration of a nonuniform flexible crane is attenuated by constructing boundary barrier-based cooperative controls and the tension restriction is guaranteed. In [18], the authors design boundary control law to restrain the deflection of a flexible string and introduce a disturbance-like term to handle the input backlash. In [19], the vibrational offset of a distributed parameter flexible aerial refueling hose is reduced via presenting boundary control scheme and the closed-loop stability is analyzed employing Lyapunov method. The backstepping approach is incorporated into the context of boundary control scheme design in [20], where the hose's vibration is prominently suppressed and the input saturation constraint is compensated. In [21], an adaptive robust boundary controller is developed to attenuate the oscillation of a flexible stretched string and compensate for the dynamical uncertainties. In [22], the vibration deflection of an axial

* Corresponding author.
** Corresponding author.
E-mail addresses: liuzhijie2012@gmail.com (Z. Liu), jingfengyang@126.com (J. Yang).

https://doi.org/10.1016/j.neucom.2017.09.050
0925-2312/

string subject to the spatiotemporally varying tension is controlled exploiting the suggested robust adaptive boundary control.

Nonsmooth input nonlinearities containing saturation, backlash, hysteresis and dead-zone are generally found in industrial control systems, such as mechanical, hydraulic, biomedical, piezoelectric, and physical systems [23–29]. The deadzone nonlinearity, which is a static input–output relationship giving zero output for a range of input values, universally exists in many control actuators and directly weakens the control effect. Neglecting the deadzone effect can lead unexpected serious problems, such as poor transient response, excessive steady state error, and large overshoot. As a consequence, it is of necessity to incorporate the deadzone nonlinearity characteristic into control design and developing an effective method to handle input deadzone effect is quite attention-getting.

In recent decades, the neural networks (NNs) have been made particularly attractive and promising for applications to tackle nonlinear systems due to requiring relatively little information of the system dynamics [30–37]. The capabilities of its universal approximation, learning and adaptation are depicted in [38–44]. In [38], robust adaptive NN control is proposed for a general class of uncertain nonlinear systems in the presence of unknown control coefficient matrices and nonsymmetric input nonlinearities of saturation and deadzone. In [39], the authors design an adaptive neural fault-tolerant control scheme to approximate the unknown nonlinear interaction functions in the large-scale system and handle the effects of the unknown dead zone. In [40], the combination of the RBFNNs and wave variable technique is employed to simultaneously compensate for the effects stemming from communication delays and dynamics uncertainties. An event-triggered state estimator is constructed for a class of discrete-time multidelayed NNs with stochastic parameters and incomplete measurements in [41], where the estimation error dynamics under the sufficient condition is exponentially ultimately bounded in the mean square. In [42], a state estimator is developed for a class of artificial neural networks without the assumptions of monotonicity or differentiability of the activation functions to ensure that the state estimation error dynamics is exponentially ultimately bounded. In [43], the output tracking error is adopted to put forward an universal adaptive fuzzy control scheme for practical tracking control of a class of nonlinear systems with unmeasured states and completely unknown perturbed dynamics. In [44], the RBFNNs based control framework and dynamic surface control technique are merged to construct a composite adaptive tracking control for eliminating the problem of explosion of complexity in a class of uncertain nonlinear systems with strict-feedback form. However, all the aforementioned works exploit the RBFNN to address the control problems for the ODE systems. To our best knowledge, despite the significant progress of boundary control for flexible systems, there is little information on employing the RBFNN to conduct the boundary control design for handling the input deadzone nonlinearity problem of the flexible string system with infinite dimensional characteristic, which motivates us for this research.

In this paper, our concerns lie in developing a boundary control for stabilizing the string system and simultaneously for coping with the effect of the input deadzone and external disturbance. The main contributions and the innovations of the paper include: (1) A basic boundary control scheme based on the backstepping method is proposed to suppress the vibration of the string system. (2) The RBFNN is employed to handle the effect of the input deadzone and the disturbance observer is exploited to track the trajectory of external disturbance. (3) The uniformly bounded stability of the controlled system is analyzed and demonstrated through rigorous Lyapunov analysis without discretizing or simplifying the dynamics in the time and space.

The arrangement of this paper is listed as below. The dynamics of the system and input deadzone nonlinearity are introduced in Section 2. Boundary control law and disturbance observer dynamics are presented in Section 3. Numerical simulations are completed in Section 4 and we reach a conclusion in Section 5. Notations are defined as follows: $(\star)(t) = (\star)$, $(\star)' = \partial(\star)/\partial x$, $\dot{(\star)} = \partial(\star)/\partial t$, $\dot{(\star)}' = \partial^2(\star)/\partial x\partial t$, $(\star)'' = \partial^2(\star)/\partial x^2$, and $\ddot{(\star)} = \partial^2(\star)/\partial t^2$.

Nomenclature

l	Length of the string
m	Mass per unit length of the string
M	Mass of the tip payload
T	Tension of the string
$z(s, t)$	Deflection of the string at the position s for time t
$z(l, t)$	Boundary deflection of the string
$\dot{z}(l, t)$	Velocity of the tip payload
$z'(l, t)$	Boundary slope of the string
$\dot{z}'(l, t)$	Time-varying rate of the boundary slope
$d(t)$	External disturbance acted on the tip payload
$u(t)$	Boundary control input applied on the tip payload

2. Problem statement

In this study, the dynamics of the considered string system shown in Fig. 1 is presented as follows [3]:

$$m\ddot{z}(s,t) - Tz''(s,t) = 0, 0 < s < l \tag{1}$$

$$z(0,t) = 0 \tag{2}$$

$$Tz'(l,t) = u(t) + d(t) - M\ddot{z}(l,t) \tag{3}$$

Consider the string system subject to the input deadzone, where the deadzone nonlinearity is described as follows:

$$u(t) = D(u_0) = \begin{cases} m_r(u_0 - b_r), & u_0 \geq b_r \\ 0, & b_l < u_0 < b_r \\ m_l(u_0 - b_l), & u_0 \leq b_l \end{cases} \tag{4}$$

where $u_0(t)$ is the control signal we will design, b_r and b_l are unknown parameters of the deadzone, and $m_r(\cdot)$ and $m_l(\cdot)$ are unknown functions of the deadzone.

Assumption 1. The deadzone parameters b_r and b_l satisfy the condition that $b_r > 0$ and $b_l < 0$.

Assumption 2. For the external disturbance $d(t)$ and first-order time differential of external disturbance $\dot{d}(t)$, we assume that there exist positive constants $\overline{d}$ and $\overline{d}_\nu$ such that $|d(t)| \leq \overline{d}$, $|\dot{d}(t)| \leq \overline{d}_\nu$, $\forall t \in [0, +\infty)$. It is a reasonable assumption as $d(t)$ and $\dot{d}(t)$ have finite energy and hence are bounded [45–47].

3. Control design

Before proceeding further, we first introduce the following coordinate transformation:

$$\omega_1 = x_1 = z(l,t) \tag{5}$$

$$\omega_2 = x_2 - \alpha = \dot{z}(l,t) - \alpha \tag{6}$$

where α is the virtual control.

Step 1. We choose the virtual control law α as

$$\alpha = -k_1\omega_1 - z'(l,t) \tag{7}$$

where $k_1 > 0$.

Then a Lyapunov candidate function is chosen as

$$V_{b1} = \frac{1}{2}\omega_1^2 \tag{8}$$

Please cite this article as: Z. Zhao et al., Neural network based boundary control of a vibrating string system with input deadzone, Neurocomputing (2017), https://doi.org/10.1016/j.neucom.2017.09.050