Journal of Sound and Vibration 406 (2017) 237–252

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Vibration control for a rigid-flexible manipulator with full state constraints via Barrier Lyapunov Function

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ARTICLE INFO

Article history:
Received 14 January 2017
Received in revised form
16 April 2017
Accepted 29 May 2017
Handling Editor: J. Lam

Keywords:
Full state constraints
Rigid-flexible manipulator
Original ODE-PDE model
Vibration suppression

ABSTRACT

Considering full state constraints, this paper designs a boundary controller for a two-link rigid-flexible manipulator via Barrier Lyapunov Function. The dynamic model of the two-link rigid-flexible manipulator is described by coupled ordinary differential equations-partial differential equations (ODEs-PDEs). Based on the original model without neglecting the high-frequency modes, boundary controller is proposed to regulate the joint positions and eliminate the elastic vibration simultaneously. To ensure that the full state constraints which include position, speed and vibration constraints are not transgressed, a Barrier Lyapunov Function is employed in the proposed controller. The asymptotic stability of the closed-loop system is rigorously proved by the LaSalle's Invariance Principle. Simulations are given to verify the effectiveness of the proposed controller with state constraints.

1. Introduction

Recently, the demand for flexible robots which have higher speed and consume less energy is greatly increasing. As a result, numerous studies on modeling and controlling for flexible manipulators have been carried out all over the world [1–3]. Inevitably, flexible structures may lead to poor performance due to the mechanical vibration and it would have a bad effect on industry system [4]. For this reason, the control of flexible manipulators still remains to be a challenge though a lot of work has been done.

The controllers for flexible manipulators are supposed to achieve the same motion objective as rigid manipulators, and also stabilize the vibrations in the meantime [5]. One indispensable step before effective controller design is to gain an accurate dynamic model for flexible manipulators [6]. The modeling problem of flexible manipulators can be roughly divided into two categories: one is finite-dimensional model described by ordinary differential equations(ODEs), and the other is infinite-dimensional model described by partial differential equations(PDEs) [7]. In fact, the vibration of a flexible link is represented by an infinite number of assumed flexible modes. The finite-dimensional model is derived by truncating the infinite number of modes to a finite number, which will neglect the higher frequency modes. Assumed Modes Method (AMM) and Finite Element Method(FEM) are often used to obtain the approximated finite dimensional models in forms of ODEs. Some well-developed controllers are proposed based on ODE model. The details can refer to [8,9]. However, the spillovers may occur due to the ignored high frequency dynamics when the controller of the truncated system is restricted to a few critical modes. As a result, a growing number of studies have focused on the controller design directly based on

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http://dx.doi.org/10.1016/j.jsv.2017.05.050
0022-460X/

Nomenclature

Nomenclature

ρ	mass density per unit
EI	uniform flexural rigidity of flexible beam
R	the position vector
u	boundary control input force
$w(x, t)$	elastic deflection of the flexible beam
$w(L_2, t)$	elastic deflection of the end of flexible beam
τ_1, τ_2	joint torques
θ_1, θ_2	joint angles of the manipulator
I_h	moment of inertia of flexible link
J_1	moment of inertia of rigid link
L_1	length of the first link
L_2	length of the second link
M_h	mass of joint
M_p	payload mass

PDEs, which are valid for the original distributed-parameter system [10–12]. For example, an observer for a flexible-link manipulator is designed in [7], which can estimate vibration and other infinite dimensional states. A P-type steady-state iterative learning control scheme is applied to the boundary control of a class of nonlinear processes described by PDEs in [13].

Conventional industrial robots typically have one or more links. The flexible one-link robotic arm is a linear system and there are quite a few studies has been conducted on vibration control or trajectory planning [14,15]. In recent years, the demand for multi-links manipulators to perform complex work is escalating. The model of multi-links robotic arm is highly nonlinear and hard to control. In this paper, the two-link rigid-flexible manipulator with a payload at the end-effector is considered. This kind of mechanical structure is widely used in modern factories. Several studies have been carried on the controller design of rigid-flexible manipulators [16,17]. A fuzzy logic controller and an efficient dynamic recurrent neural network for a two-link rigid-flexible manipulator are proposed in [18]. An novel approach for dynamics modeling of rigid-flexible multi-body systems has been studied in [19].

For common physical systems, the constraint characteristics are generally existing due to the limitation of mechanical system components and security factors. The violation of physical constraints may lead to poor performance, machine damage or other serious hazards. Existence of these harmful phenomena will make it more difficult and more complicated to design effective controllers in industrial conduction [20].

Existing methods to handle state and output constraint include reference governor [21], model predictive control [22] and extremum-seeking control [23]. Besides that, a means of obtaining a non-overshooting output tracking response strict-feedback nonlinear systems is introduced in [24]. In further development, a Barrier Lyapunov Function is employed to settle the problem of output constraint [25,26]. For a class of continuous stirred tank reactor with output constraint and uncertainties, an adaptive control approach is proposed in [27] based on the Barrier Lyapunov Function. In spite of these effective methods, works of two-link manipulators based on PDE dynamic model with output constraint are relatively few.

In this paper, a controller for a two-link rigid-flexible manipulator is designed in this paper. Full state constraints problems which include position, speed and vibration constraints is considered. Related work has been published in [28]. Boundary control laws are developed in [28] to stabilize the transverse vibration for a nonlinear vertically string system with output constraint. There is no coupling between the rotation angle and vibration since the rotation angle of the flexible string system is fixed. In this paper, we consider a two-link rigid-flexible manipulator system. In this system, coupling relationship not only exists between rigid and flexible parts but also between the rotation angle and elastic vibration. It is necessary to design a boundary controller which can regulate the joint positions and eliminate the elastic vibration simultaneously. Studies on the coupled system with full state constraints are significant whether in theory research or practical application. The results and contributions of this study are as follows.

(1) A coupled ODE-PDE dynamic model for a rigid-flexible two-link manipulator is presented. Based on the original ODE-PDE model, boundary control is designed to regulate the joint positions and eliminate the elastic vibration simultaneously.
(2) Motivated by the fact that many mechanical systems are under the constraints due to safety specifications, the full state constraints problem is considered. Barrier Lyapunov Function(BLF) which grows to infinity whenever its arguments approach to some limits is introduced in the control laws. With the help of BLF, full states of the system stay bounded.
(3) Asymptotic stability of the two-link rigid-flexible manipulator is proved by LaSalle's Invariance Principle.

It is interesting to note that all the analysis of the controller design and stability proof are based on the original nonlinear ODE-PDE dynamic model, without neglecting higher modes.

The paper is organized as follows. Section 2 introduces the coupled ODE-PDE dynamic model for a two-link rigid-flexible manipulator. By using a Barrier Lyapunov Function and LaSalle's Invariance Principle, Section 3 proposes the boundary controller and gives rigorous proof of the asymptotic stability. Numerical simulation results are shown in Section 4 and the conclusions are given in Section 5.