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Adaptive tracking control for stochastic mechanical systems with actuator nonlinearities

Huihui Pan[a,b], Weichao Sun[a,*], Xingjian Jing[b,c]

[a] Research Institute of Intelligent Control and System, Harbin Institute of Technology, Harbin 150001, China
[b] Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong, China
[c] Hong Kong Polytechnic University, Shenzhen Research Institute, Shenzhen, China

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Abstract

In this paper, output tracking control problem is investigated for a class of uncertain nonlinear random mechanical systems subjected to unknown actuator nonlinearities. Two common kinds of actuator nonlinearities, namely, Bouc–Wen hysteresis and dead-zone, are considered in a unified framework, such that the designed adaptive control law is robust to the mentioned actuator nonlinearities (hysteresis and dead-zone). Different from some existing controller design approaches for nonlinear systems with actuator nonlinearities, the usual priori knowledge on the known compact set for system uncertain parameters has been eliminated with the proposed control method. The proposed control law can ensure that the system output tracking error eventually converges to an arbitrarily small neighborhood of zero in the sense of mean square by turning controller gains. Simulation studies are performed to demonstrate the effectiveness of the proposed controller design approach.

1. Introduction

Recently, the control of nonlinear systems with non-smooth input nonlinearity has become one active research topic since control input signals are usually subjected to some practical

* Corresponding author.
E-mail addresses: huihuipan0@gmail.com (H. Pan), w.sun@hit.edu.cn (W. Sun), xingjian.jing@polyu.edu.hk (X. Jing).

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restrictions. Especially many actuators possess non-smooth nonlinear properties, for example electric servomotors, mechanical connections, piezoelectric translators, hydraulic servo-valves, and other areas [1–6]. Such actuator nonlinearities are difficult to control since they act regularly as a source of performance deterioration and even result in instability and undesirable oscillations or inaccuracy. Traditional control approaches are not sufficient to handle the unknown non-smooth characteristics of inputs. Thus, the development of control approaches for nonlinear systems subjected to actuator nonlinearities has attracted considerable attention and become a significant topic in the control community for decades. Importantly, the adaptive control law design for different kinds of uncertain systems subjected to actuator nonlinearities has been of theoretical significance and practical interest task in recent years [7–12].

The common types of input nonlinearities in practical applications include hysteresis and dead-zone, which generally hold non-smooth and highly nonlinear characteristics [13–15]. Numerous studies have been developed to address these problems. To mention a few, in the framework of adaptive control, the authors in [15] have provided a novel hysteresis inverse compensation model, based on the assumption that the actuator parameters are exactly known in the Bouc–Wen hysteresis model, which can guarantee the output tracking error tends to zero. In spite of that, the adaptive approach presented in [15] is still conservative in some ways, since some strong assumption conditions are required to be meet. Robust adaptive backstepping controller was proposed in [16] for uncertain nonlinear systems subjected to dead-zone, where the system stability was ensured by Lyapunov functions. However, the prevalent methods on the control system design with input nonlinearities are only appropriate for nonlinear deterministic system without external stochastic disturbance, which limits their practical applications.

Practically, random disturbance always exists in practical mechanical systems and engineering applications [17–24], which can severely limit system performance in an uncertain manner. Thus, the research on stability analysis and controller design for stochastic nonlinear systems is a meaningful issue. In the developments of stochastic control theory, an increasingly recognized method is, especially by introducing the quartic Lyapunov function [25,26], the backstepping method which was proposed for strict-feedback random nonlinear systems with state- and output-feedback control. This controller design scheme became one of the well-accepted approaches to resolve control issues for stochastic nonlinear systems. Some stochastic mechanics [27,28], and the references therein, studied the properties and control methods of mechanical systems in presence of random noise.

Motivated by the analysis above [13–16,28–31], the main concern of this study is the issue of adaptive output tracking for random mechanical systems subjected to parametric uncertainties and unknown input nonlinearities. A unified control approach is presented to handle the Bouc–Wen hysteresis and dead-zone nonlinearities. In this control scheme, the unknown actuator nonlinearities are divided into an unknown parameter multiplied by the control signal with a disturbance-like term. Furthermore, it can be verified that the disturbance-like term in the unified nonlinear actuator model is bounded by a constant. By the employment of this unified actuator model, a new adaptive control method is thus proposed for a class of uncertain nonlinear stochastic mechanical systems without using the inverse function of input nonlinearity. Moreover, prior knowledge of actuator nonlinear parameters (e.g., slopes and break-points) are not needed to be known, this can greatly facilitate the presented controller design method to be more appropriate for practical engineering applications.

Notations. $\mathbb{R}^+$, $\mathbb{R}^n$ and $\mathbb{R}^{n\times r}$ denote the family of all nonnegative real number, n-dimensional Euclidean space and the $n \times r$ real matrix space, respectively. $\mathcal{K}$ denotes