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Adaptive control for continuous-time systems with actuator and sensor hysteresis[☆]

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ABSTRACT

This paper discusses the model reference control for a continuous-time linear plant containing uncertain hysteresis in both actuator and sensor devices. The difficulty of controlling such systems lies in the fact that the hysteretic uncertainties exist in both the input and the output of the plant, the genuine input and genuine output of the plant are not available, while the ultimate goal is to control the plant output which may not be correctly measured. New adaptive control schemes with the actuator uncertainty and sensor uncertainty compensations are developed for linear plants with either known or unknown dynamics, where adaptive estimates of the genuine outputs of the plants are simultaneously generated. The global stability analysis of the closed-loop system becomes very complicated and challenging, and the proposed control laws ensure the uniform boundedness of all signals in the closed-loop system. The tracking error between the estimated plant output and the desired output is guaranteed to converge to zero asymptotically.

1. Introduction

In the past two decades, smart materials have been well and widely studied in the industrial and academic fields. Since most of the smart materials have a bidirectional property between electric field and mechanical force, they can be used as actuators and sensors. So far, smart material-based actuators and sensors have received much attention due to their excellent characteristics and promising applications. For example, piezo actuators (Croft, Shed, & Devasia, 2001) and magnetostrictive actuators (Natale, Velardi, & Visone, 2001; Tan & Baras, 2004) can be applied to ultra-high precision positioning to meet the requirements of nanometer resolution in displacement, high stiffness and rapid response; shape memory alloys (Gorbet, Morris, & Wang, 2001; Nespoli, Besseghini, Pittaccio, Villa, & Viscuso, 2010; Romanoa & Tannurib, 2009) can be applied to robotics and active vibration control systems, to meet the requirement of low energy consumption, long lifetime, etc; ionic polymer metal composite (IPMC) actuators (Chen & Tan, 2010, 2011) are expected to be used as artificial muscles to meet the requirement of low energy consumption, noiselessness, flexibility, lightness. On the other hand, piezo sensors (Yong, Fleming, & Moheimani, 2013) and magnetostrictive material-based sensors (Jia, Liu, Wang, Liu, & Ge, 2011) are used to meet the requirement of heavy load, rapid response, low power consumption, downsizing, better capability to adapt to harsh working environment,etc; IPMC sensors (Chen, Tan, Will, & Ziel, 2007; Ganley, Huang, Zhu, & Tan, 2011) are expected to meet the requirement of low energy consumption, lightness, medical applications, etc. However, it is reported that a non-smooth and nonmemoryless strong nonlinear phenomenon "hysteresis" exists between the input and output of all the smart material-based actuators and sensors (see Banks & Smith, 2000; Cross, Krasnosel'skii, & Pokrovskii, 2001; Drincic, Tan, & Bernstein, 2011; Hanawa, Wang, Deng, & Jiang, 2012; Mayergoyz, 1991; Moheimani & Goodwin, 2001; Natale et al., 2001; Seco, Martin, Pons, & Jimenez, 2004; Smith, 2005; Webb, Lagoudas, & Kurdila, 1998) and the corresponding hysteresis nonlinearities are usually unknown in practice. As a result, the outputs of the actuators and the inputs of the sensors become unknown signals in practice since the actuators are usually used to actuate the plants

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as an input directly and the sensors are usually used to measure the plant output directly. When the hysteretic nonlinearity exists in systems, the system usually exhibits undesirable inaccuracies or oscillations and even instability (Tao & Kokotovic, 1995a,b).

For the systems driven by actuators with uncertain hysteresis, the control problem has received considerable attention recently Ren, Ge, Su, and Lee (2009); Tao and Kokotovic (1995a); Wang, Chen, Liu, Liu, and Lin (2014); Wang and Su (2006); Wen and Zhou (2007); Zhou, Wen, and Zhang (2004) and Zhou, Wen, and Li (2012). The common control approach pioneered by Tao and Kokotovic (1995a) is to construct an inverse hysteresis model to compensate the effect of the hysteresis. Essentially, the inversion problem depends on hysteresis modeling methods. Since the hysteresis in the smart material-based actuators are very complicated with multivalues and non-smooth features where the operator-based hysteresis models such as Prandtl–Ishlinskii model and Preisach model (Visintin, 1994) are usually applied, the hysteresis inversion then becomes very challenging. In order to mitigate this difficulty, another approach is proposed in Chen, Hisayama, and Su (2010) where an adaptive implicit inversion of the hysteresis is introduced and updated in accordance with the parameters in the controller which can stabilize the closed-loop system.

When output signals measured by sensors with uncertain hysteresis are used in feedback control systems, the development of the controllers is another difficult task because the genuine output of the plant is not available and the eventual purpose is to control the output of the plant. The control techniques reported in the literature until now are surprisingly spare. A pioneer work is Tao and Kokotovic (1995b) where a special hysteretic uncertainty "backlash" is considered. By constructing an adaptive backlash inverse, the uniform boundedness of the signals in the closed-loop system is assured. Another important work is Parlangeli and Corradini (2005) where the considered hysteresis can be described by ten parameters. By using the sliding mode robust control method, output zeroing is achieved.

By considering the fact that smart material-based actuators and sensors are widely used currently, it is necessary to address the challenge for the control design of the system in presence of both actuator and sensor hysteresis. The difficulty of controlling this class of systems lies in the fact that the hysteretic uncertainties exist in both the input and the output of the plant, the genuine input and genuine output of the plant are not available, and the ultimate goal is to control the plant output which is not an available signal. About the regulation problem for the continuous-time systems in the presence of actuator and sensor uncertain hysteresis, a pioneer work is Parlangeli and Corradini (2005) where the considered hysteresis is relatively simple and can be characterized by ten parameters. It should be mentioned that the control for discrete-time linear plant containing uncertain hysteresis in both actuator and sensor devices has been discussed in Tao (1996) and Chen and Ozaki (2010). However, the controller design for continuous-time system is not simply an extension of its counterpart, and the designs for continuous-time system and discrete-time system are based on different strategies. Furthermore, since rapid sampling of a continuous-time linear plant will always give rise to a non-minimum phase discrete-time linear system (Astrom & Wittenmark, 1997) and the results until now (Chen & Ozaki, 2010; Tao, 1996) are limited to minimum phase discrete-time plants, the continuous-time plant is adopted in this paper to avoid this difficulty.

In this paper, the model reference control for a continuous-time linear plant containing uncertain hysteresis in actuator and sensor devices simultaneously is discussed, where Prandtl–Ishlinskii (PI) model is used to express the hysteresis nonlinearity. The adoption of PI model is based on the fact that it can describe the

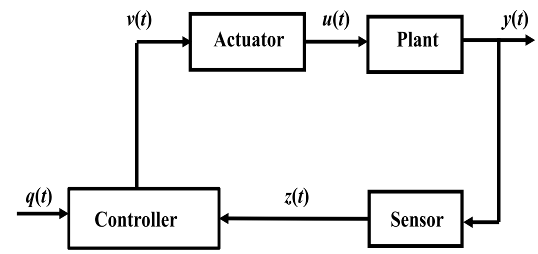

Fig. 1. Block scheme of the considered system.

hysteresis existing in smart materials, especially the typical hysteresis behavior in piezo actuators (see Chen & Hisayama, 2008; Krejci & Kuhnen, 2001) and IPMC materials (Hanawa et al., 2012), and possesses the unique inverse property (Krejci & Kuhnen, 2001). In the developed scheme, new adaptive control schemes with the actuator uncertainty and sensor uncertainty compensations are developed for linear plants with either known or unknown dynamics, where adaptive estimates of the genuine outputs of the plants are simultaneously generated. Only the parameters directly needed in the formulation of the controller are adaptively estimated online. The proposed control laws ensure the uniform boundedness of all signals in the closed-loop systems. Furthermore, the tracking error between the estimated plant output and the desired output is guaranteed to converge to zero asymptotically. Generally, the zero convergence of the tracking error between the genuine plant output and the desired output cannot be guaranteed. Finally, the proposed algorithms are illustrated by simulation examples.

The organization of the paper is as follows. Section 2 formulates the problem of model reference tracking in the presence of unknown actuator and sensor hysteresis nonlinearities and gives the Prandtl–Ishlinskii (PI) hysteresis model. In Section 3, adaptive control schemes are developed for plants with either known or unknown dynamics. In Section 4, simulation results are presented to illustrate the proposed algorithms. Section 5 concludes this paper.

2. Problem statement

2.1. System description

Consider the adaptive control for the continuous-time plant driven by an actuator with hysteresis and measured by a sensor with hysteresis shown in Fig. 1.

The considered system is described by

$$y(t) = G(s)[u](t) = k_p \frac{Z(s)}{P(s)}[u](t), \tag{1}$$

$$u(t) = H_1[v](t), \tag{2}$$

$$z(t) = H_2[y](t), \tag{3}$$

where $y(t) \in R$ is the genuine output of the linear plant which is also the input of the sensor, $u(t) \in R$ is the input of the linear plant which is also the output of the actuator, $v(t) \in R$ is the input to the actuator, $z(t) \in R$ is the output of the sensor which is also the measured output of the linear plant; $H_1[\cdot]$ and $H_2[\cdot]$ are the PI hysteresis operators whose structure will be given in the next subsection; $G(s)$ is the transfer function of the linear plant, k_p is the high frequency gain, $P(s)$ and $Z(s)$ are described by the following polynomials.

$$P(s) = s^{n_0} + p_{n_0-1}s^{n_0-1} + \cdots + p_1 s + p_0, \tag{4}$$

$$Z(s) = s^m + z_{m-1}s^{m-1} + \cdots + z_1 s + z_0, \quad n_0 > m. \tag{5}$$

R denotes the space of real numbers.