Control Engineering Practice 33 (2014) 148–160

Contents lists available at ScienceDirect

Control Engineering Practice

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

Modeling and inverse adaptive control of asymmetric hysteresis systems with applications to magnetostrictive actuator

Zhi Li [a], Chun-Yi Su [a,*], Xinkai Chen [b]

[a] Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Canada
[b] Department of Electronic and Information Systems, Shibaura Institute of Technology, Minuma-ku, Saitama-shi, Saitama 337-8570, Japan

ARTICLE INFO

Article history:
Received 4 February 2014
Accepted 9 September 2014
Available online 17 October 2014

Keywords:
Asymmetric hysteresis
Asymmetric shifted Prandtl–Ishlinskii (ASPI) model
Prescribed adaptive control
Magnetostrictive actuator

ABSTRACT

When uncertain systems are actuated by smart material based actuators, the systems exhibit hysteresis nonlinearities and corresponding control is becoming a challenging task, especially with magnetostrictive actuators which are dominated by asymmetric hystereses. The common approach for overcoming the hysteresis effect is inverse compensation combining with robust adaptive control. Focusing on the asymmetric hysteresis phenomenon, an asymmetric shifted Prandtl–Ishlinskii (ASPI) model and its inverse are developed and a corresponding analytical expression for the inverse compensation error is derived. Then, a prescribed adaptive control method is applied to mitigate the compensation error and simultaneously guaranteeing global stability of the closed loop system with a prescribed transient and steady-state performance of the tracking error without knowledge of system parameters. The effectiveness of the proposed control scheme is validated on a magnetostrictive actuated platform.

1. Introduction

Hysteresis is a nonlinear phenomenon that appears in many different areas. Ferromagnetic hysteresis (Brokate & Sprekels, 1996) and plastic hysteresis (Jiles & Atherton, 1986) are two typical examples. Hysteresis exhibited in the smart material-based actuators, such as magnetostrictive and piezoelectric actuators (Smith, 2005), reveals a looped and branched nonlinear relation between the input excitation and the output displacement. Hysteretic behaviors also arise in aerodynamics, where the aerodynamic forces and moments show hysteresis when the attack angle of the airplane varies. Others are encountered in mechanical systems, economics, neuroscience and electronics engineering (Esbrook, Xiaobo, & Khalil, 2013; Xiao & Li, 2013), etc. When a control system involves the hysteresis nonlinearity such as actuated by smart material-based actuators, the hysteresis nonlinearity generates an undesired and detrimental effect, which will deteriorate the system performance and cause inaccuracy or oscillations. The common approach for remedying its effect is to construct a hysteresis inverse in putting in cascade as a compensator to cancel the hysteresis effect (Krejci & Kuhnen, 2001; Kuhnen, 2003; Li, Hu, Liu, Chen, & Yuan, 2012). For constructions of the hysteresis inverse, two approaches are generally used: direct construction of complete inverse function of the hysteresis function (model) (Krejci & Kuhnen, 2001; Kuhnen, 2003), and use of an inverse multiplicative structure (Rakotondrabe, 2011; Zhou, Wen, & Li, 2012) of the models to compensate the complicated component in the model, in which the development of the complete inverse function of the hysteresis model is not required. Direct construction of inverse function of the hysteresis model is mainly for operator based models such as Preisach (1935) model and Prandtl–Ishlinskii (PI) model (Krejci & Kuhnen, 2001). In both, the hysteresis is modeled by a superposition of elementary relay or play operators. However, only the PI model possesses the analytic form of the inverse (Krejci & Kuhnen, 2001), which explains why the PI model is becoming dominant in the direct inverse compensation approaches. In this paper, we will focus on the direct inverse approaches owing to unknown function in hysteresis models.

It is recognized that the operator based models except the Preisach model generally describe the symmetric hysteresis effects. However, there are many cases that the hysteresis exhibits asymmetric behaviors such as magnetostrictive actuators, shape memory alloys (SMA) actuators. To keep the feature of PI model with the analytic inverse, the extension of the PI model to describe the asymmetric hysteresis behavior has been exploited in the literature, including (1) cascading a nonlinear operator with the PI model. In Kuhnen (2003), a modified PI model, superposition of one-sided dead-zone operators proceeded by the PI model, was proposed. This model can describe the asymmetric hysteresis behavior and has analytical solutions of its inversion, but it cannot describe the saturated hysteresis behaviors; (2) modifying the elementary play operator. In Jiang, Ji, Qiu, and Chen (2010), the elementary play operator was redefined as right-side play operator

* Corresponding author.
E-mail address: cysu@alcor.concordia.ca (C.-Y. Su).

http://dx.doi.org/10.1016/j.conengprac.2014.09.004
0967-0661/

and left-side play operator. In Jiang, Deng, and Inoue (2008), a non-symmetric play operator was considered as the elementary operator. In Janaideh, Mao, Rakheja, Xie, and Su (2008), a generalized play operator with envelope functions was proposed, where the analytical inversion was provided with requirement of first-order derivative of the input signals.

To avoid the drawbacks of the those PI extensions and preserve the advantage of the existing analytic inverse of the PI model while still being able to describe the asymmetric hysteresis behavior, an asymmetric shifted Prandtl–Ishlinskii (ASPI) model is proposed in this paper, which is constructed by three components: a PI model, a shift model and an auxiliary function. The advantages of the proposed model are (1) it is able to represent the asymmetric hysteresis behavior; (2) it facilitates the construction of the analytic inverse by directly utilizing the available PI inverse result in Krejci and Kuhnen (2001) without the requirement of first-order derivative of the input signals; (3) the analytical expression of the error of the inverse compensation can be derived for the asymmetric case, which will be explained as follows.

As reported in the literature, using the inverse for hysteresis compensation generally exhibits notable compensation errors, which are attributed to hysteresis characterization errors. The use of an estimated hysteresis model in deriving the model inverse would be expected to yield some degree of hysteresis compensation error. This error yields tracking error in the closed-loop control system. To accommodate such a compensation error, the analytical expression of the error of the inverse compensation is urged in the controller design. Along this line, in Tao and Kokotovic (1993, 1995) the analytical inverse compensation error for backlash hysteresis was derived and a corresponding adaptive control scheme was then developed. For the PI model, an analytical error expression was obtained and an adaptive backstepping control scheme was developed in Janaideh, Su, and Rakheja (2012). However, the analytical error expression was obtained only for the PI model, it has not yet being exploited for its extensions. Therefore, as listed in the third advantage, the inverse compensation error for the proposed ASPI model is analytically derived for the purpose of the controller design when the nonlinear system is preceded by the asymmetric hysteresis. In order to ensure the transient and steady-state performance of the tracking error a prescribed adaptive control scheme is employed. The developed prescribed adaptive control approach guarantees the global stability of the nonlinear system and achieves the prescribed transient and steady-state performance of the tracking error without knowledge of system parameters. To validate the developed ASPI model and the adaptive inverse hysteresis control scheme, experimental results on a magnetostrictive actuated platform are presented.

2. Problem statement

Consider a dynamic nonlinear system consisting of an actuator with hysteresis nonlinearity $\Pi[v](t)$ and a nonlinear plant as

$$x^{(n)}(t)+\sum_{i=1}^{k} a_i Y_i(x(t),\dot{x}(t),\ldots,x^{(n-1)}(t)) = bu(t) \tag{1}$$

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

where $v(t)$ denotes the input and $u(t)$ denotes the output, Y_i are known continuous, linear or nonlinear functions. Parameters a_i and control gain b are unknown constants, $\Pi[v](t)$ denotes the output of the hysteresis operator, which will be described in the following development.

The control objective is to design a control signal $v(t)$ for system (1), such that:

P1: The system state $x(t)$ tracks a desired signal $x_d(t)$ and all signals in the closed-loop are bounded;
P2: Both transient and steady-state performance of tracking error $e_1(t)=x(t)-x_d(t)$ should be within the prescribed area.

Comparing with general nonlinear control for the system (1) only, the control signal $u(t)$ becomes the output of the hysteresis operator $u(t)=\Pi[v](t)$, where the actual control signal is $v(t)$. As it is well known, the hysteresis nonlinearity will deteriorate the system performance and cause inaccuracy or oscillations. Therefore, it imposes a challenge to handle this cascaded term with a basic requirement that $u(t)$ is not available/measurable. The common approach for remedying the effect is to construct a hysteresis inverse as a feedforward compensator. Then the control law can be designed with available control methods. The complete control scheme is shown in Fig. 1.

Throughout the paper the following standard assumptions are required:

Assumption 1. The sign of uncertain parameter b is known. Without losing generality, it is selected as $b>0$ in this paper.

Assumption 2. The desired trajectory $x_d(t)$ and its $(n-1)$th-order derivatives are continuous. Furthermore, $[x_d,\dot{x}_d,\ldots,x_d^n]^T \in \Omega_d \subset R^{n+1}$ with Ω_d being a compact set.

3. Modeling and inverse construction of asymmetric hysteresis

3.1. The Prandtl–Ishlinskii (PI) model

The Prandtl–Ishlinskii (PI) model was first used for describing the hysteresis behavior of elasto-plasticity by Prandtl in 1928, which is defined as Brokate and Sprekels (1996)

$$P[v](t)=p_0 v(t)+\int_0^{\Lambda} p(r)F_r[v](t)\,dr \tag{3}$$

where p_0 is a positive constant; $p(r)$ is a given density function, satisfying $p(r)\geq 0$ with $\int_0^\infty rp(r)\,dr<\infty$. Since the density function $p(r)$ vanishes for large values of r, the choice of Λ as the upper limit of integration in the literature is just a matter of convenience (Su, Wang, Chen, & Rakheja, 2005). $F_r[v]$ is the play operator:

$$F_r[v](0)=f_r(v(0),0) \tag{4}$$

$$F_r[v](t)=f_r(v(t),F_r[v](t_i)) \tag{5}$$

for $t_i<t\leq t_{i+1},\ 0\leq i\leq N-1$, with

$$f_r(v,w)=\max(v-r,\min(v+r,w)) \tag{6}$$

where $0=t_0<t_1<\cdots<t_N$ is a partition of $[0,t_N]$, such that the function $v(t)$ is monotone on each of the subintervals $[t_i,t_{i+1}]$.

The main feature of the PI model is its unique property of being analytically invertible (Krejci & Kuhnen, 2001), which makes it possible to utilize its inverse as a feedforward compensator to cancel the hysteresis effect. However, it should be noted that owing to the definition of the play operator, the PI model can only describe symmetric hysteresis (Brokate & Sprekels, 1996).

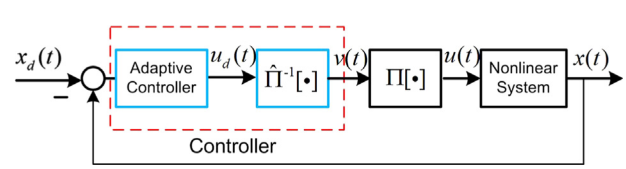

Fig. 1. The control scheme.