Analysis and Design of Indirect Adaptive Fuzzy Controller for Nonlinear Hysteretic Systems

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Abstract In order to handle the nonlinear properties of hysteretic systems, an indirect adaptive fuzzy controller (IAFC) is proposed in this paper. However, it is hard to directly identify the unknown hysteretic effects. Therefore, to overcome this problem, a dynamic hysteretic equation is employed and modified to construct the nonlinear properties of backlash-like hysteretic systems. Besides, the existence of an IAFC can be derived in this paper. Compared with the existing fuzzy control methods, our proposed IAFC is simpler and can handle the more general hysteretic problems with our new learning algorithm. Based on the learning algorithm, the adaptive and the control laws not only can be derived but the stability of the closed-loop system can also be guaranteed by the Lyapunov stability criterion. Finally, the proposed IAFC is compared to the adaptive backstepping control method, and the results show that our proposed IAFC can effectively handle the nonlinear properties in the backlash-like hysteretic systems.

Keywords Backlash-like hysteretic system · Hysteretic effect · Indirect adaptive fuzzy controller · Lyapunov stability · Adaptive backstepping control

1 Introduction

In mechanical systems, hysteresis and dead zone are two kinds of input nonsmooth nonlinearities which will degrade the performance of the systems. These nonlinear phenomena exist in many physical systems and materials, such as ferroelectric and ferromagnetic materials, mechanical actuators, electronic throttles, and other related fields [1–7]. Although hysteresis and dead zone commonly coexist, they have different nonlinear properties, actually. Hence, in this paper, we only discuss the hysteretic nonlinearities. In fact, different types of hysteresis have totally different nonlinear properties. Thus, we focus mainly on the hysteresis model called “backlash-like hysteresis.” Backlash-like hysteresis is usually found in the mechanical systems, which causes a delay between the input force and output response. To control the systems with unknown backlash-like hysteresis is quite important but typically challenging. Incidentally, conventional control methods are insufficient to deal with the nonlinear systems with these non-smooth nonlinearities [8]. For simplicity, the hysteresis is sometimes ignored in the controller design. However, ignorance of nonlinear hysteresis will lead to the obvious steady-state error, oscillation, and even instability. Hence, the development of alternate effective approaches is required and urging.

For research purpose, the foremost task is to find a model to describe the hysteretic nonlinearities, which helps us to design a proper controller. Until now, the research on mathematical models for unknown hysteresis is still an ongoing topic. Thus, there are various models being proposed in past decades, and different hysteresis models will affect the effectiveness of the control algorithms. Generally, the existing hysteresis model can be roughly categorized into two types [9]: operator-based hysteresis models and differential equation-based hysteresis models. The operator-
based models use integral equations which contain numerous hysteresis operators and can describe the shapes of hysteresis curves accurately. The popular operator-based models are Preisach model [10], Prandtl-Ishlinskii (PI) model [11], etc. For differential equation-based models, they have finite dimensions and can be extend to continuous inputs using approximation [9], which can reduce the computational complexity effectively. The models like Bouc-Wen model [12], Duham model [9], and Backlash-like model [13] are used widely in the controller design for hysteretic problems. For nonlinear hysteretic properties in our benchmark problems, the backlash-like model proposed in [13] is adopted with a little modification throughout this paper to model our problems.

Based on the mathematical models, several alternate approaches have been proposed in [13–21] in past decades. The above methods used the adaptive control schemes to mitigate the nonlinear effects of hysteresis. In [14–16], an adaptive inverse operator was constructed to cancel the backlash nonlinearity, but the strict initial conditions were required. In [21], a smooth inverse function combined with the backstepping technique was utilized to compensate the nonlinear effects of the backlash. Using the intelligent control schemes like fuzzy logic control (FLC) or neural network (NN) has been depicted in [17–19]. Those intelligent control methods have the advantage of excellent nonlinearity approximation, which can eliminate the inversion error [17–19]. Some experimental applications showed that backlash inverters would degrade the system control performance [22, 23]. Hence, a controller design scheme without constructing the inverse operator has been proposed in [13, 18, 20]. In [18] and [13], a continuous dynamic backlash-like hysteresis model was defined. However, the backlash-like term multiplying the control in [18] and [13] must be bounded, and the uncertain parameters must also be within known intervals. The adaptive backstepping control methods proposed in [20] strive to eliminate the above restrictions. Some more complex problems and methods can be found in [24–26].

A new indirect adaptive fuzzy controller (IAFC) using "feedback + feed-forward" scheme is proposed to mitigate the hysteretic phenomenon without the above restrictions. Besides, a dynamic backlash-like hysteresis model is utilized in the nonlinear systems with unknown nonlinear control gain which is more general than that in [13]. The existence of the IAFC for the unknown hysteretic system is first shown in Theorem 2. The adaptive laws of IAFC are constructed based on the Lyapunov stability theory, and the IAFC control law guarantees that all the signals of the closed-loop system are stable. Finally, the proposed IAFC is compared with the adaptive backstepping control method, and the results demonstrate that our proposed IAFC has better effectiveness and excellent tracking performance.

This paper is organized as follows: Sect. 2 states the problem of this paper, where the nonlinear backlash-like model is introduced. In Sect. 3, the proposed IAFC scheme is presented. In Sect. 4, the simulation results are presented. Finally, in Sect. 5, conclusions are drawn.

2 Problem Formulation

2.1 System Model

We consider the following nth-order SISO nonlinear system described by the differential equations which are more general than that in [13] and [20]:

\[
\begin{align*}
\dot{x}_i &= x_{i+1}, \quad i = 1, \cdots, n-1 \\
\dot{x}_n &= F(x) + g(x)\omega(t) \\
y &= x_1
\end{align*}
\]

(1)

where \( x = [x_1, x_2, \cdots, x_n]^T = [\dot{x}, \ddot{x}, \cdots, x^{(n-1)}]^T \in \mathbb{R}^n \) is the measurable state vector; \( u \in \mathbb{R} \) and \( y \in \mathbb{R} \) are the input and the output of the system, respectively; \( F(x) = -\sum_{i=1}^r a_if_i(x) \); and parameters \( a_i \) are unknown but bounded constants \( f_i(x) \) and control gain \( g(x) \) are unknown nonlinear functions. (1) has to be controllable so we require that the control gain \( g(x) \neq 0 \). Besides, without losing generality, it is assumed that \( g(x) > 0 \). In [13], the control gain \( g \) is simply an unknown constant, and functions \( f_i \) have to be known linear or nonlinear functions. The function \( \omega(t) \) is the output of the nonlinear hysteresis. Incorporating this hysteretic function into our system model, a nonlinear hysteretic system is formed and the system schematic diagram is shown in Fig. 1.

The control objective is to design a control law for \( u(t) \) in (1) and an adaptive law for adjusting the parameter vector, such that the system output \( x \) can track the reference signal \( y_m \). Note that the reference signal \( y_m \) is assumed to be \((n-1)\)th differentiable.

2.2 Backlash-like Model and Its Characteristics

A continuous dynamic model to simulate the hysteretic phenomenon defined by [13] can be described by

![Fig. 1 Representation of the nonlinear hysteretic system](image-url)