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Sensors and Actuators A 119 (2005) 254–262
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Modeling hysteresis using hybrid method of continuous transformation and neural networks

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Received 18 February 2004; received in revised form 14 September 2004; accepted 24 September 2004
Available online 27 October 2004

Abstract

A novel and simple approach to modeling hysteresis nonlinearities is proposed. The continuous transformation technique is used to construct an elementary hysteresis model (EHM), which forms a one-to-one relation between the input space and the output space of hysteresis nonlinearities. In theory, we can apply the output of the EHM as one of the input signals of a common neural network (NN) to approximate any kind of hysteresis nonlinearities, which meet any input signals satisfying an assumption. In order to validate the effectiveness of the proposed approach we use several sets of data from the proposed backlash-based hysteresis simulation models (BHSMs) for respective simulation testing. Then a set of real data measurements is used to evaluate the proposed approach. These results of simulation testing indicate that the proposed approach is simple and successful.

Keywords: Hysteresis nonlinearity; Modeling; Continuous transformation; Neural network

1. Introduction

In controlled systems, hysteresis can cause a number of undesirable effects, including loss of stability robustness, limit cycles and steady-state error and so on. Major hurdles control designers must overcome when faced with hysteresis nonlinearity are obtaining an accurate tractable model of the hysteretic behavior, and finding corresponding means of analysis and design capable of dealing with nonlinear and non-single-valued behavior. Various models have been proposed to describe the hysteresis in literatures. However, the use of the numerical Preisach model to describe the nonlinear hysteresis behavior of magnetic materials has been proven to be an effective way in many papers [1–6].

In the recent decade, artificial neural networks (NNs) have been widely and successfully used in many fields, including hysteresis modeling. However, both theory [7] and practice have proven that hysteresis nonlinearities cannot be approximated via traditional approach of NN. Therefore, either modifying NN or using several NNs becomes a basic choice. For instance, Nafalski et al.[8] suggested using NN as an entire substitute for hysteresis models. Wei and Sun [7] proposed a novel neural network cell as the propulsive neural unit. Taga et al. [9] developed a network containing six coupled oscillators (as neurons) to control two-wheeled locomotive. The locomotive will exhibit hysteresis when movement transition occurs. Hwang et al. [10] utilizes two neural networks to approximate the descending and ascending parts of hysteresis loops, respectively. It can be seen that they are basically limited to some simpler results, such as single loop or first-order reserve curves. Little is found in the literature on the dynamic hysteresis model, which

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doi:10.1016/j.sna.2004.09.019

can adapt to any input signals and any types of hysteresis behavior.

In this paper, the objective of this work is to use a simple approach to construct a neural network hysteresis model, which can predict dynamically any types of hysteresis behavior and adapt to any input signals satisfying an assumption. Firstly, according to the principle of the classic Preisach model, several kinds of dynamic backlash-based hysteresis simulation models (BHSMs) are proposed. Then, through observing and analyzing the process of Preisach hysteresis curves, we find some characteristics and rules of the moving points of hysteresis nonlinearities. Therefore, we can adopt the continuous transformation approach to construct an elementary hysteresis model (EHM). Based on this EHM, without changing the structure, we use a common two-input–one-output NN to approximate the actual hysteresis curve, i.e., to construct an EHM-based NN hysteresis model.

The rest of this paper is organized as follows: In the next section, the theory of the classical Preisach model is briefly described and several kinds of BHSMs are proposed. In Section 3, we depict the modeling approach and idea, and construct the mapping relation between inputs of NN and actual hysteresis nonlinearities. Implementation of the EHM and several testing examples are presented to validate the effectiveness of the proposed approach in Section 4. Section 5 concludes this work.

2. Formulation of the Preisach model and construction of BHSMs

The Preisach operator is a mathematical construction that has been used successfully over the years to model the phenomenon of hysteresis occurring in magnetics, superconductivities, and elasto-plastic deformations, etc. Though it does not provide any physical insight into the physical phenomenon, it provides a means of developing phenomenological models that are capable of producing behavior similar to physical systems. It is of great interest to the smart structures and controls community because of its utility in developing low order models that can be used for designing real-time controllers.

The main assumption made in classical Preisach model is that the system can be thought of as a parallel summation of a continuum of weighted relay hysteresis $\gamma_{\alpha\beta}$. Each relay is characterized by the pair of switching values (α, β), with $\alpha > \beta$, so that there is a unique representation of the collection of relays as points in the half-plane $p = \{(\alpha, \beta)|\alpha > \beta\}$ (Fig. 1). The Preisach model can be mathematically expressed as follows [2–4]:

$$f(t) = \iint \mu(\alpha, \beta)\gamma_{\alpha\beta}u(t)\mathrm{d}\alpha\, \mathrm{d}\beta, \tag{1}$$

where $f(t)$ is the model output at time t, $u(t)$ is the model input at time t, and $\gamma_{\alpha\beta}$ can only assume the values +1 or −1. Model (1) may be reasonably approximated by a finite superposition of different operators. The behavior of these relays, and hence the Preisach model, is only defined for continuous input u. As this input varies with time, each individual relay adjusts its output according to the current input value, and the weighted sum of all the relay output provides the overall system output.

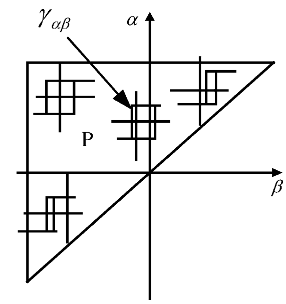

Fig. 1. The Preisach plane.

According to the relations between the input–output curve and Preisach plane, we have the following analysis and observation results shown in Fig. 2. We assume initially that the input $u(t)$ is 0, and the hysteresis model is in the “down” position (with an output of 0) Fig. 2(a). When the input increases from point 0 to 1(Fig. 2(a) and Fig. 2(b)), i.e., the first maximum value is point 1, the curve (a) moves up along major loop until the input decreases, and the diagram in P plane is that horizontal line moves up to 1–2′(c and d). Then, the input decreases from 1 to 2, i.e., the first minimum value is point 2, and the curve (a) moves down along minor loop 1–2. The descending segment of the first minor loop is produced (a, 1–2), and the diagram in P plane shows that the vertical line moves down from 1 to 2–2′ (c and d). When input $u(t)$ increases from 2 to 3 and 4, the ascending segment is generated (a, 2–3) and the first minor loop is enclosed. The process has traversed the small triangle 1–2′–2(c and d) twice, and its area corresponds to the area of the enclosed minor loop (a, 1–2–3) and the vertical height between point 3 and point 2 in the curvilinear triangle (b, 1–2–3). The input increases to 4 and removes the previous maximum value 1, which is the “wiping out property” of the Preisach hysteresis model. The posterior processes are analogous with that described above, (d), (e) and (f) show the diagrams of P plane as the input runs to 4, 6 and the end, respectively. If the vertical height between points 3 and 2 in the curvilinear triangle (b, 1–2–3) equals the vertical height between points 6 and 7 in the curvilinear triangle (b, 5–6–7), it leads that the area of two triangles (c, 1, 3–2′–2 and 5, 7–6–5′) is also equal. Thus, the two minor loops will be congruent. This is the “congruent minor loop property” of the Preisach hysteresis model. These two properties serve as the necessary and sufficient conditions for the existence of a Preisach model [2–4].

Inspired by the theory of Preisach hysteresis model described above, we can apply many backlash models to construct a hysteresis simulation model. They may be called Backlash-based hysteresis simulation model (BHSM). The backlash nonlinearity model is given by [11]