Precision Engineering 38 (2014) 921–927

Contents lists available at ScienceDirect

Precision Engineering

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

Online parameter identification of the asymmetrical Bouc–Wen model for piezoelectric actuators

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ARTICLE INFO

Article history:
Received 9 March 2013
Received in revised form 4 June 2014
Accepted 10 June 2014
Available online 18 June 2014

Keywords:
Piezoelectric actuator
Asymmetrical Bouc–Wen model
Online parameter identification
Recursive least-squares method
Limited memory method

ABSTRACT

The hysteresis of piezoelectric actuators (PAs) possesses the asymmetrical and frequency-dependent characteristics. In order to accurately model the hysteresis of a PA, an asymmetrical Bouc–Wen model is proposed and established in this paper. The recursive least-squares online identification method is used to real-time identify the parameters of the proposed model. Meanwhile, in order to avoid the data saturation phenomenon, the limited memory method is used to limit the number of the data sets. The experimental system is setup and the performance of this method is experimentally verified. Experimental results show that the proposed online identification method can effectively improve the modeling accuracy.

1. Introduction

Piezoelectric actuators (PAs) based on inverse piezoelectric effect are widely used in precision positioning due to their small size, high energy density, high positioning accuracy, high resolution, and quick frequency response [1–4]. However, the hysteresis between the output displacement and the applied voltage from and to a PA seriously affects the positioning accuracy. In the current literatures, the hysteresis models can be categorized into the physical and mathematical models. Through analyzing the inherent mechanism of hysteresis of piezoelectric layers, the physical models [5,6] which could provide a theoretical basis for designing and controlling PAs were established. However, the physical models are relatively complicated because their inherent mechanism is quite complex. The mathematical models include the Preisach model [7,8], the Prandtle-Ishlinskii model [9,10], the polynomial approximation [11], the Duhem model [12], the Maxwell slip model [13], the Jiles–Atherton model [14], the LuGre model [15], and the Bouc–Wen model [16–19].

Because the Bouc–Wen model can match the behavior of a wide class of hysteresis systems [20], it has been extensively adopted in many engineering fields to represent the hysteresis behavior of engineering elements and structures [21–24]. However, there are some difficulties in the application on the PA. For example, existing Bouc–Wen models cannot describe the highly asymmetric and the frequency-dependent hysteresis of a PA. To account for the strong asymmetry, Zhu and Wang [16] put forward an asymmetrical Bouc–Wen model by introducing an asymmetrical formula into the Bouc–Wen hysteresis operator. To avoid the large modeling error, Ha et al. [17] proposed the Bouc–Wen model to model a piezo-actuated positioning mechanism which only works in the single frequency. In order to improve the control accuracy, Gomis-Bellmunt et al. [18] offline identified the parameters of the Bouc–Wen model in a certain frequency range which can make the Bouc–Wen model adapt the certain frequency.

In this paper, an asymmetrical Bouc–Wen model for a PA will be proposed and established. The recursive least-squares online identification method will be used to real-time identify the parameters of the asymmetrical Bouc–Wen model.

2. Asymmetrical and frequency-dependent characteristics of the hysteresis of a PA

2.1. Asymmetrical characteristics of the hysteresis and the asymmetrical Bouc–Wen model

Fig. 1 shows the measured hysteresis curve of a PA under a 1 Hz sinusoidal voltage. The output displacement in the stable period is different from that in the initial period due to the memory of piezoelectric materials. Considering the fitted line in least-squares sense as the linear component, the hysteresis curve shown in Fig. 2 can be decomposed into a linear component ($X(t)$) and a hysteretic

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http://dx.doi.org/10.1016/j.precisioneng.2014.06.002
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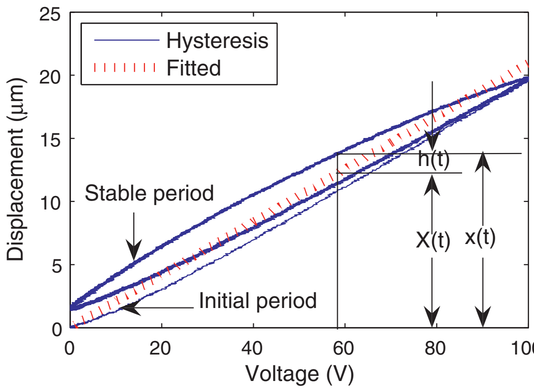


Fig. 1. Measured hysteresis curve of a PA under a 1 Hz sinusoidal input voltage.

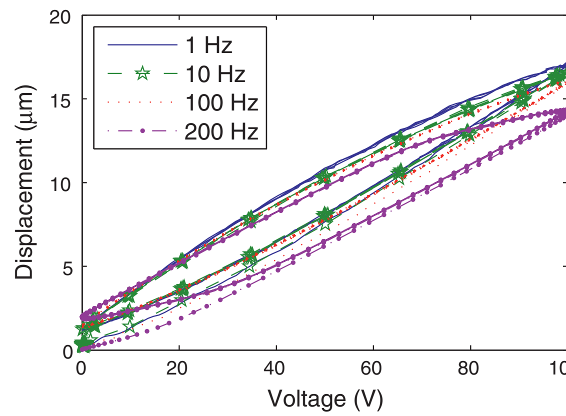


Fig. 3. Frequency-dependent hysteresis of the PA.

component ($h(t)$), which are plotted in Fig. 2(a) and (b), respectively. Observing Fig. 2, the hysteresis curve can be considered as the superposition of the linear component and the hysteretic component. The burr in the hysteretic component as shown in Fig. 2(b) is mainly attributable to the external disturbances in the measurement process. Obviously, the curve shown in Fig. 2(b) demonstrates the significant asymmetry in the hysteretic component of the PA.

From Fig. 2, the output displacement from the PA can be given by

$$x(t) = X(t) + h(t) \tag{1}$$

$X(t)$ is governed by

$$X(t) = k_v u(t) + x_0 \tag{2}$$

where $u(t)$ denotes the input voltage; k_v is a constant representing the ratio between the output displacement and the input voltage; x_0 is the initial displacement. Substituting Eq. (2) into Eq. (1), then

$$x(t) = k_v u(t) + x_0 + h(t) \tag{3}$$

Using the Bouc–Wen hysteresis operator [25] to simulate the hysteretic component

$$\dot{h}(t) = A\dot{u}(t) - \beta|\dot{u}(t)||h(t)|^{n-1}h(t) - \gamma\dot{u}(t)|h(t)|^n \tag{4}$$

where the dot at the top of variables represents the first order derivative with respect to time; A, β, γ, and n are the parameters of the Bouc–Wen hysteresis operator. The model for the PA defined by Eqs. (3) and (4) is called the Bouc–Wen model.

To model the asymmetrical hysteresis, a formula to represent the asymmetrical characteristic is introduced into the Bouc–Wen hysteresis operator. Eq. (4) can be rewritten as [16]

$$\dot{h}(t) = A\dot{u}(t) - \beta|\dot{u}(t)||h(t)|^{n-1}h(t) - \gamma\dot{u}(t)|h(t)|^n + \delta u(t)sgn(\dot{u}(t)) \tag{5}$$

where δ is the asymmetry factor; $\delta u(t)sgn(\dot{u}(t))$ is the asymmetrical formula;

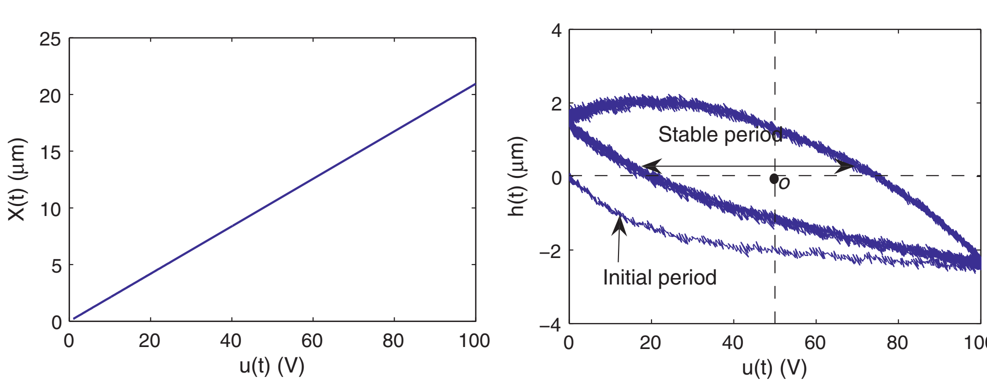
$$sgn(\dot{u}(t)) = \begin{cases} 1 & \dot{u}(t) > 0 \\ 0 & \dot{u}(t) = 0 \\ -1 & \dot{u}(t) < 0 \end{cases}$$

Eqs. (3) and (5) define the asymmetrical Bouc–Wen model. In order to use the asymmetrical Bouc–Wen model to simulate the hysteresis of a PA, the parameters k_v, x_0, A, δ, β, n, and γ need to be identified.

2.2. Frequency-dependent behavior of the hysteresis

We apply a set of sinusoidal voltages with different frequencies to the PA, and the hysteresis of the PA is frequency-dependent, which becomes more evident with the increase of input frequencies as shown in Fig. 3. The hysteresis curves of the asymmetrical Bouc–Wen model under different input frequencies are shown in Fig. 4, which indicates the asymmetrical Bouc–Wen model cannot characterize the frequency-dependent hysteresis of the PA.

In order to improve modeling accuracy, the parameters of this model are identified by an online identification method (in Section 3), which make the asymmetrical Bouc–Wen model can describe the frequency-dependent hysteresis.



(a) (b)

Fig. 2. Linear and hysteretic components of the hysteresis curve of the PA: (a) the linear component and (b) the hysteretic component.