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Non-linear compensation and displacement control of the bias-rate-dependent hysteresis of a magnetostrictive actuator

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ABSTRACT

Magnetostrictive actuators invariably exhibit bias-rate-dependent hysteresis, which could cause vibration and error in the micro-positioning control. We present a methodology for linearization control for the hysteresis of a magnetostrictive actuator with a wide range of input rates and biases. The hysteresis compensation is attained through application of a dynamic Bouc-Wen model and experimental measured hysteresis properties of the magnetostrictive actuator under inputs with different frequencies and biases. The effectiveness of the compensator for hysteresis is demonstrated through experimental results of the magnetostrictive actuator under inputs at different frequencies and bias levels. Based on the proposed compensator, a displacement PID controller is applied to force the output displacement of the magnetostrictive actuator to track the desired displacement accurately thereafter. The maximum absolute tracking errors is 0.052 μm. Compared to the control results without the compensator, the compensator can reduce the control error by about 85%. The results indicate that this study provides an effective method which can compensate the hysteresis of the magnetostrictive actuator under different frequencies and biases of inputs.

1. Introduction

Magnetostrictive actuators are increasingly being explored for various nano-positioning and vibration control applications due to their fast response and relatively large stroke and force capacity [1–4]. The presence of the hysteresis, however, imposes difficulties in achieving precise positioning of these actuators. The hysteresis is known to cause instability and tracking errors in open- and closed-loop control systems [5,6]. Thus, it is highly desirable to cancel out the hysteresis so that magnetostrictive devices can have a virtually linear relationship or one-to-one mapping between the input current and the output displacement. Hysteresis compensation can be achieved by formulating a hysteresis model that can describe the output-input characteristics of the actuator and an inverse based on the model itself which can be applied experimentally on the actuator [7,8].

Although, the physics-based hysteresis models provides reasonable predicting for the hysteresis nonlinearities [9], these models are not invertible which poses difficulties in compensating hysteresis nonlinearities of smart material actuators. On the other hand, the phenomenological hysteresis models, such as the Preisach model [10], the LuGre model [11], the Duhem model [12], the Maxwell model [13], and the Bouc-Wen model [14,15], allow formulating an inverse that can be employed for compensation of the hysteresis of smart actuators. Because the Bouc–Wen model can match the behavior of a wide class of hysteretic systems, it has been extensively adopted in many engineering fields to represent the hysteresis behavior of engineering elements and structures [16]. The Bouc–Wen model uses a non-linear differential equation to describe the hysteresis and gives a broad range of possibilities for model-based controller design. These studies show that the output-input properties of magnetostrictive actuators depend on several experimental factors like bias level [17] and frequency of the input [18]. These phenomenological hysteresis models including the Bouc-Wen model, however, are difficult to accurately reflect the bias-rate-dependent hysteresis of magnetostrictive actuators. The application of inverse rate-independent hysteresis models would thus yield considerable compensation errors under excitations at higher frequencies and biases. It is thus desirable to formulate an accurate hysteresis model and its inverse considering a broad range of input rates and biases [19,20]. Therefore, in order to effectively and accurately control the output displacement of the magne-

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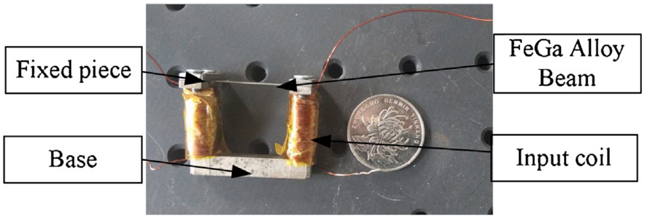

Fig. 1. Magnetostrictive actuator.

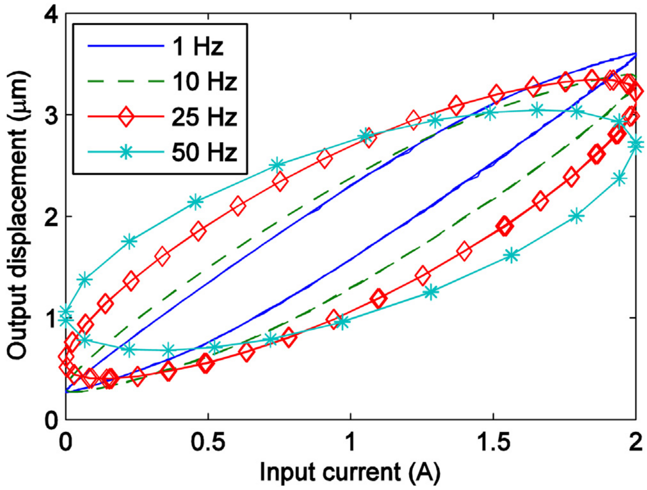

Fig. 2. Measured hysteresis of the magnetostrictive actuator under inputs $I = \sin(2f\pi t) + 1$ ($f = 1, 10, 25, 50$ Hz).

tostrictive actuator, it is very important to put forward a hysteresis model to accurately represent the bias-rate-dependent hysteresis.

The primary aim of this study is to develop a dynamics Bouc-Wen model capable of considering the input bias and rate effects and then use the inverse based on the proposed model itself to compensate the bias-rate-dependent hysteresis. This paper is organized as follows: Section 2 details the hysteresis characteristics of a Fe-Ga alloy magnetostrictive actuator; Section 3 develops a dynamics Bouc-Wen model to describe bias-rate-dependent hysteresis, while Section 4 introduces a non-linear feedforward compensator; the displacement PID control method with the proposed compensator is establish in Section 5; Section 6 shows experimental results and analysis of the non-linear compensation and displacement control, and Section 7 concludes the work.

2. Characterization of hysteresis of a magnetostrictive actuator

Fig. 1 shows a Fe-Ga alloy magnetostrictive actuator. Both ends of the Fe-Ga alloy beam are fixed to the base by the fixed pieces. When applying a current to input coil of the actuator, the magnetostrictive force of the beam, due to the magnetostriction effect, results in the forced vibration of the actuator. The number of turns, resistance, and inductance of the input coil is 200, 0.62 Ω, and 0.21 mH, respectively. The material of the base is the pure iron and its relative magnetic permeability is about 7000. Experiments are performed on the magnetostrictive actuator to measure its hysteresis characteristics by laser Doppler vibrometer (LDV, type: OFV-505/5000, Produced by Polytec GmbH, measurement range: −20 to + 20 μm, resolution: 1 nm, non-linearity: 0.05%, bandwidth: 0–1.5 MHz) under excitations in the 1–50 Hz frequency and 1–3 A bias range, which are shown in Figs. 2 and 3, respectively. Those figures show that the magnetostrictive actuator exhibits asymmetric hysteresis that are strongly dependent upon the rate and bias of the input current. Thus, increasing the frequency of the applied input increases the hysteresis of the actuator, while increasing the input bias reduces hysteresis.

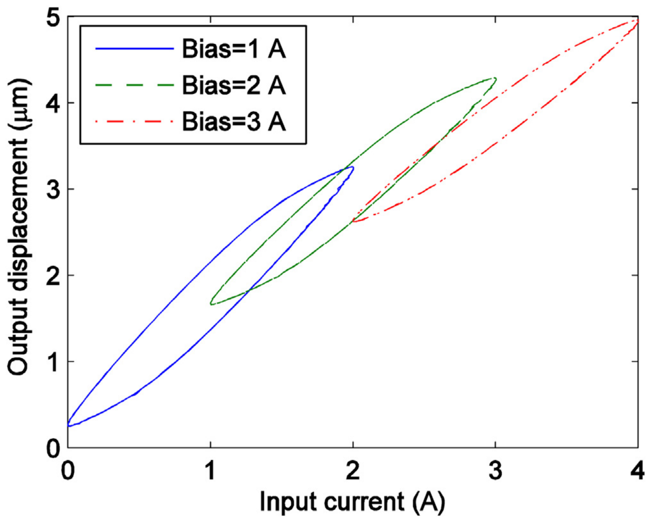

Fig. 3. Measured hysteresis of the magnetostrictive actuator under input of 1 A amplitude applied at 5 Hz and three levels of current bias: 1, 2, and 3 A.

Table 1
Parameters of the dynamic Bouc-Wen model identified by the method proposed in reference [21].

$k_l(I_b) = (2.18 - 0.324I_b) \times 10^{-6}$	$\tau = 0.0029$	$\alpha = -20.6$	$\beta = 1.48$
$k_h(I_b) = (5.39 - 1.13I_b) \times 10^{-8}$	$\gamma = -0.99$	$n = 1.12$	

3. Dynamic Bouc-Wen model

The traditional Bouc-wen model proposed by references [22] can be expressed in a unified form as

$$x = k_l I + k_h h \quad (1)$$

$$\dot{h} = \left\{\alpha - \left[\beta sgn\left(\dot{I}h\right) + \gamma\right] |h|^n\right\} \dot{I} \quad (2)$$

where x is the output displacement of the actuator; I is the input current, k_l is the constant ratio between the linear displacement and input current; h is the hysteretic force, k_h is the constant ratio between the hysteresis displacement and hysteresis force; $\dot{h}$ and $\dot{I}$ are the first order derivatives of h and $\dot{I}$ with respect to time, respectively; α, β, γ, and n shape the form of the hysteresis loop.

However, the measured data, shown in Section 2, indicate that the magnetostrictive actuator exhibit bias-rate-dependent hysteresis. In this study, in order to minimize modeling error, a dynamic Bouc-Wen model is proposed by introducing a frequency factor, two bias functions and can expressed as

$$x = \left(1 - e^{-t/\tau}\right) \left[k_l(I_b) I + k_h(I_b) h\right] \quad (3)$$

$$\dot{h} = \left\{\alpha - \left[\beta sgn\left(\dot{I}h\right) + \gamma\right] |h|^n\right\} \dot{I} \quad (4)$$

where t is the time; τ is the frequency factor that represents the frequency characteristics of the input coil and Fe-Ga alloy; $k_l(I_b)$ and $k_h(I_b)$ are functions which describe the relationships between the linear force and the bias current.

Using the experimental data shown in Figs. 2 and 3 and the parameter identification method proposed in reference [19], the parameters of the dynamic Bouc-Wen model are listed in Table 1.

The validity of the proposed model is explored by comparing the model output displacement with those of the measured data. As Fig. 4 illustrate, the proposed model can effectively predict the

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