

# Hysteresis Modeling for Magnetic Shape Memory Alloy Actuator via Pi-Sigma Neural Network with Backlash-Like Operator

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Magnetic shape memory alloy materials have a bright prospect in micro-nano intelligent actuators, however, the hysteresis in these materials is prevalent and damages the positioning precision of these actuators. In this paper, a Pi-Sigma neural network model with a modified backlash-like operator is developed to capture the dynamic hysteresis of the magnetic shape memory alloy material actuator. The modified backlash-like operator is designed for the multi-value-mapping and asymmetrical hysteresis of the magnetic shape memory alloy material actuator. The rate-dependent hysteresis of the magnetic shape memory alloy material actuator is described via the Pi-Sigma neural network model. Experimental results show that the effectiveness of the proposed model outperforms the Krasnosel'skii–Pokrovskii model.

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## 1. Introduction

Magnetic shape memory alloy (MSMA) is a new functional material, in which the martensite reorientation induced by the external magnetic field makes the twin boundary move, appearing micro displacement macroscopically [1]. Furthermore, these materials can generate magnetic strain up to 12%, and have merits of fast response and strong controllability [2, 3]. These features make MSMA materials suitable to manufacture intelligent actuators. However, the hysteresis in MSMA materials severely damages the output accuracy of driven actuators based on MSMA materials [3]. In order to study the hysteresis in MSMA material actuators deeply, hysteresis modeling methods take on even more importance. There are three types of hysteresis models, which include operator-based models, differential equation-based models, and intelligent neural network-based models [4]. Nevertheless, operator-based and differential equation-based models cannot describe the dynamic hysteresis of MSMA material actuators, and neural network-based models can only solve one-to-one and multi-to-one nonlinearity mapping problems. The contribution of this study is not only to solve multi-value-mapping and asymmetrical hysteresis problems in the MSMA material actuator via a modified backlash-like operator, but also the rate-dependent hysteresis problem of the MSMA material actuator via the Pi-Sigma neural network (PSNN). The availability of the proposed model is testified by a series of contrast experiments. Experimental results show that the proposed model can describe both the dynamic hysteresis and asymmetrical major-minor hysteresis loops of

the MSMA material actuator and achieve a better performance compared with the Krasnosel'skii–Pokrovskii (KP) model in [5].

## 2. Hysteresis model of the MSMA material actuator

The static hysteresis curves with multi-value-mapping and asymmetrical characteristics of the MSMA material actuator are shown in Fig. 1a, and Fig. 1b shows the rate-dependent dynamic hysteresis curves of the MSMA material actuator. According to Fig. 1a, the MSMA material actuator has different output values under the same input current (i.e.,  $I = 1.2$  A), showing the multi-value-mapping characteristic, and response curves of the MSMA material actuator are not symmetric about the centerline, showing the asymmetrical characteristic. As shown in Fig. 1b, the maximum output displacement decreases and the hysteresis loop widens as the input current frequency increases so that the rate-dependent characteristic is exhibited.

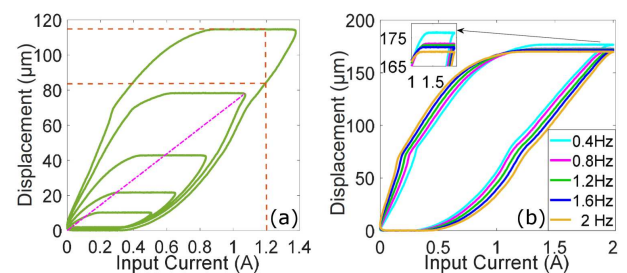


Fig. 1. Hysteresis characteristic curves of the MSMA material actuator: (a) multi-value-mapping and asymmetrical characteristics, (b) rate-dependent characteristic.

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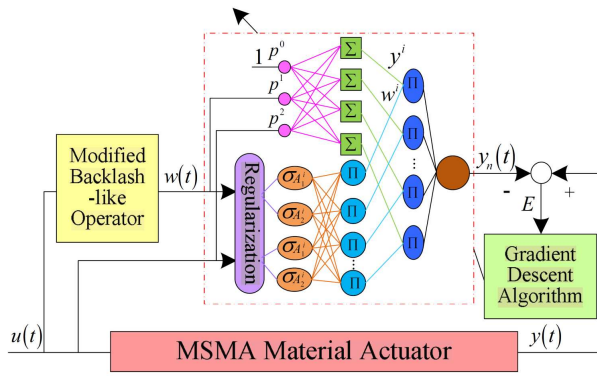


Fig. 2. Schematic diagram of the proposed model for the MSMA material actuator.

To solve multi-value-mapping and asymmetrical hysteresis problems of the MSMA material actuator, we define a modified backlash-like operator by introducing the exponential and polynomial function as

$$\begin{aligned} dw/dt &= \alpha |du/dt| \left( c \exp \left( -(u - \beta)^2 / \gamma \right) - w \right) \\ &+ du/dt (b_0 + b_1 u + b_2 u^2), \end{aligned}$$

where  $u$  and  $w$  are the input and output of the modified backlash-like operator, respectively,  $\alpha$ ,  $c$ ,  $\beta$ ,  $\gamma$ ,  $b_0$ ,  $b_1$ , and  $b_2$  are constants obtained by the shuffled frog leaping algorithm [6].

The rate-dependent hysteresis problem of the MSMA material actuator can be solved by the nonlinearity mapping ability of PSNN. Figure 2 is the schematic diagram of the proposed model.

The input of the PSNN is  $X = [x_1(t), x_2(t)]$ . The rule is introduced into the PSNN as: if  $x_1(t)$  is  $A_1^i$ ,  $x_2(t)$  is  $A_2^i$ , then  $y^i(t) = p_0^i + p_1^i x_1(t) + p_2^i x_2(t)$ , where  $A_j^i$  is the fuzzy subset,  $p_r^i$  is the truth-value,  $y^i(t)$  is the output obtained by the rule,  $j = 1, 2$ ;  $r = 0, 1, 2$ ;  $i = 1, 2, \dots, m$ . The output of the PSNN is given by:  $y_n(t) = \sum_{i=1}^m w^i y^i(t) / \sum_{i=1}^m w^i$ , where  $m$  is the node number of the hidden layer,  $w^i$  is the truth-value acted on the input according to the rule as:  $w^i = \prod_{j=1}^2 \sigma_{A_j^i}(x_j(t)) = \exp \left( \sum_{j=1}^2 \left( -(x_j(t) - \mu_j^i)^2 / a_j^i \right) \right)$ , where  $\sigma_{A_j^i}(x_j(t))$  is the membership function value,  $\mu_j^i$  and  $a_j^i$  are the central vector and sound stage width, respectively. The cost function of the PSNN is defined as:  $E(t, \theta) = (y(t) - y_n(t, \theta))^2 / 2$ , where  $y(t)$  is the actual output of the MSMA material actuator.  $\theta = [(p_r^i), (\mu_j^i), (a_j^i)]^T$  is the parameter updated by the gradient descent algorithm as:  $\theta(t+1) = \theta(t) - \eta \partial E(t, \theta) / \partial \theta + \tau [\theta(t) - \theta(t-1)]$ , where  $\eta > 0$  is the learning factor,  $\tau \in [0, 1)$  is the momentum term. The gradients of  $E(t, \theta)$  with respect to  $p_r^i$ ,  $\mu_j^i$ , and  $a_j^i$  are deduced as follows:

$$\frac{\partial E}{\partial p_r^i} = -(y - y_n) w^i x_j / \sum_{i=1}^m w^i, \quad (1)$$

$$\begin{aligned} \frac{\partial E}{\partial \mu_j^i} &= -2(y - y_n) \left( y^i \sum_{i=1}^m w^i - \sum_{i=1}^m (w^i y^i) \right) \\ &(x_j - \mu_j^i) w^i / a_j^i \left( \sum_{i=1}^m w^i \right)^2, \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial E}{\partial a_j^i} &= -(y - y_n) \left( y^i \sum_{i=1}^m w^i - \sum_{i=1}^m (w^i y^i) \right) \\ &(x_j - \mu_j^i)^2 w^i / (a_j^i)^2 \left( \sum_{i=1}^m w^i \right)^2. \end{aligned} \quad (3)$$

### 3. Experimental results

In the experiment, the output displacement of MSMA material (Ni-Mn-Ga, 2 mm×3 mm×14 mm) actuator is controlled by the external magnetic field generated via the driving current in a coil to achieve the conversion between electric, magnetic, and mechanical energy. The experimental equipment is shown in Fig. 3. To build the dynamic hysteresis model and describe asymmetrical major-minor hysteresis loops, firstly, we utilize a sinusoidal current signal with different frequencies  $I = 0.7 \sin(2\pi ft - 0.5\pi) + 1.4$  (i.e.,  $f = 1, 5, 10$  Hz) and a variable amplitude mixed frequency sinusoid current signal  $I = (0.6 \sin(\pi t - 0.5\pi) + 1.1)(0.8 \sin(1.6\pi t - 0.5\pi) + 1.5)$  to drive the MSMA material actuator via the Power; then, the output displacement of the MSMA material actuator is measured using the linear variable differential transformer (LVDT). Finally, the input-output data is collected by the data acquisition card (PCI-1716). The hysteresis between the output displacement and the input current is modeled online by the PSNN with 2, 9, and 1 nodes in the input, hidden, and output layers, respectively. The parameters are set as:  $\eta = 0.85$ ,  $\tau = 0.4$ ,  $\alpha = -0.8179$ ,  $c = -0.3111$ ,  $\beta = 0.2146$ ,  $\gamma = 0.2126$ ,  $b_0 = 0.9259$ ,  $b_1 = -0.5209$ , and  $b_2 = -0.3337$ .

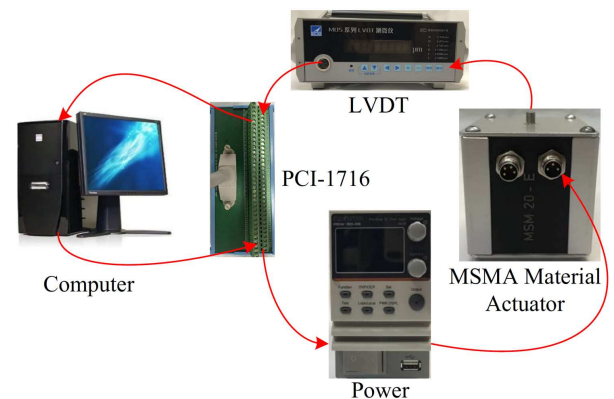


Fig. 3. Experiment equipment diagram.

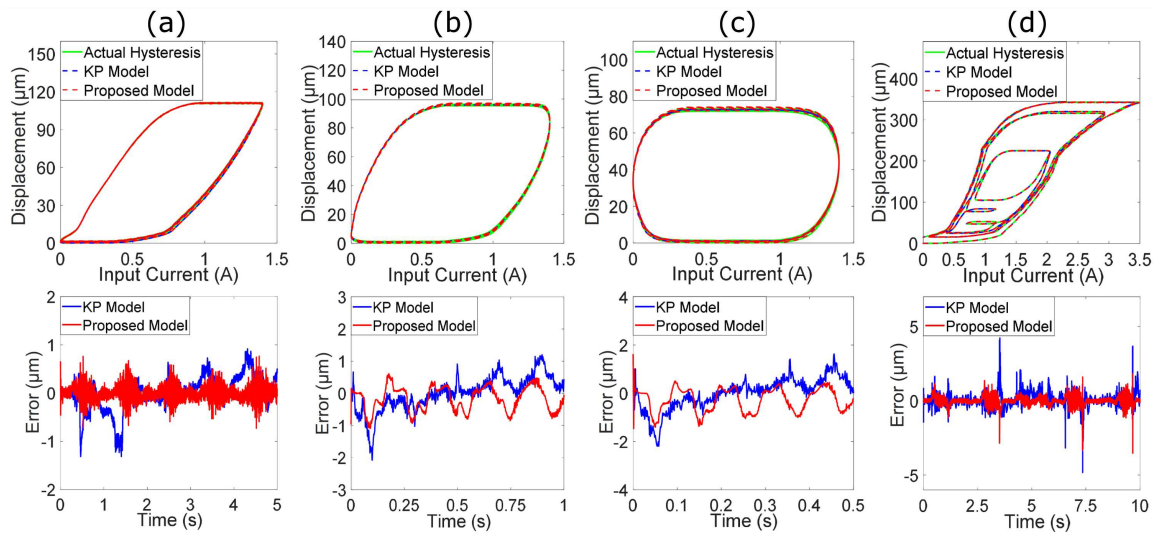


Fig. 4. Experimental results of the KP model and the proposed model: (a) 1 Hz, (b) 5 Hz, (c) 10 Hz, (d) variable amplitude mixed frequency sinusoid current signal.

The comparative experimental results are shown as Fig. 4. In Fig. 4, the green solid line is the actual hysteresis loops of the MSMA material actuator based on experimental data. The blue dash line and red dash line are the hysteresis loops of the KP model and the proposed model, respectively. The blue solid line and red solid line represent the errors of the KP model and the proposed model compared with experimental data, respectively. We can draw a conclusion that the proposed model is more precise to capture the dynamic hysteresis of the MSMA material actuator under different frequency driving currents compared with the KP model in [5]. When the input is the variable amplitude mixed frequency sinusoid current signal, the comparative result is shown as Fig. 4d. As shown in Fig. 4d, the proposed model can describe asymmetrical major-minor hysteresis loops of the MSMA material actuator in a better performance compared with the KP model. To further certify the effectiveness of the proposed model, the root-mean-square error (RMSE), mean absolute error (MAE), and maximal error rate (MER) are calculated. Compared with the KP model, the MAE of the proposed model is decreased by 60%, 16%, and 14%, and the MER of the proposed model is reduced by 42%, 47%, and 31% when frequencies are 1 Hz, 5 Hz, and 10 Hz, respectively. The RMSE, MAE, and MER of the proposed model are lowered by 52%, 57%, and 27% when describe both the major and minor asymmetrical hysteresis loops of the MSMA material actuator in comparison to the results of [5].

#### 4. Conclusions

To study the hysteresis in the MSMA materials, this paper proposed a hysteresis modeling approach via the PSNN with a modified backlash-like operator.

Experimental results show that the modeling precision of the proposed model is greatly increased compared with the KP model. In conclusion, the proposed model is a good method for applications in the MSMA material sensors and actuators and further researches on the MSMA materials.

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