Parameter identification of a modified dynamical hysteresis model with immune clone algorithm

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Abstract This paper focuses on application of immune clone algorithm to identify parameters of a modified dynamical hysteresis model for giant magnetostrictive materials (GMM). The domain flexing function proposed by Damijan Miljavec et al, is added into this model, which resulted in one extra parameter, to overcome the unphysical negative susceptibility problem. Thus, the immune clone algorithm is applied to identify the parameters in this revised model. The efficiency of the parameter identification with immune clone algorithm is verified by comparing the model generated curves between the identified parameters and the selected parameters. Moreover, it can be seen the unphysical behavior of minor hysteresis loop is suppressed by comparing the identified model curve with the original model curve and a set of representative experimental data.

Keywords Parameter identification, Immune clone method, Hysteresis, Minor loop

1. Introduction

Some magnetic materials when located in an applied magnetic field can elongate or contract in magnetization direction due to an induced magnetic field in these materials. The generated strains are attributed to the realignment of a large amount of magnetic domains caused by spontaneous magnetization. This phenomenon is called magnetostriction. Giant magnetostrictive materials (GMM) have some distinctive advantages over other smart materials, for example, the ability to generate large forces at a lower voltage than piezoelectric ceramic material (PZT), to react more rapidly than shape memory alloy (SMA), to keep their properties even been grinded into particles. Such distinctive advantages motivate many researchers to investigate the applications of GMM in many aspects such as high power ultrasonic transducers, linear motors, micro pumps, micro valves, micro positioners and active vibration absorbers[1-2].

To utilize the full potential of GMM in practical applications, the intrinsic nonlinear magnetic-elastic-thermal coupling properties and hysteresis behavior of GMM need be described clearly. Thus, different models, including physical-based and nonphysical ones [3-5], have been proposed to describe the unique characteristics of GMM. Extended from the most typical physical-based J-A model, Zheng and her co-workers proposed a new model [6] in which nonlinear magnetic-elastic-thermal coupling properties and hysteresis behavior are displayed clearly. However, like the J-A model, this new model encountered the same parameter problem in choosing optimal parameters. Thus, a general method to obtain the optimal parameters is needed for this constitutive relation of GMM.

Generally speaking, two kind methods to overcome the parameter problem of J-A model have been proposed. First, a step-by-step methodologies based on the physical meaning of the determinable parameters are available [7]. But this classic procedure sensitive to initial values of parameters and the order of evaluation of the equations, may pose convergence problem as noticed in [8]. Second, a mathematical approach of the parameter identification disregarding the physical background works in the parameters state-space and tries to find the optimal combination of the parameters [9-12]. The main idea of using immune clone method to optimization problem is heuristic searching in the trusted solution space and recording the optimal solution in each iteration step until no better solution can be found [13-14]. Thus, adopt the immune clone method to do parameter identification is feasible.

The aim of the present paper is to provide an alternative estimation procedure of parameters based on immune clone algorithm for the modified dynamical hysteresis model of GMM. In section 2 the dynamical magnetic-elastic-thermal coupled hysteresis model is modified by introducing the domain flexing function. Then the immune clone algorithm is adopted to identify the parameters in this devised model in section 3. The immune clone algorithm is verified by comparing the identified model curve with the reduced static model generated curve. In section 4, by comparing the identified model curve with a set of representative experimental data the unphysical behavior of minor hysteresis loops are suppressed.

2. Dynamic hysteresis model and the domain flexing function

The following form of dynamic hysteresis model is considered [6]:

$$\begin{aligned}&\frac{\mu_0 d^2}{2\rho\tilde{\beta}}\left(\frac{dH}{dt}\right)\left(\frac{dM}{dH}\right)^2+\left(\frac{GSV_0\mu_0}{\rho}\right)^{1/2}\left(\frac{dH}{dt}\right)^{1/2}\left(\frac{dM}{dH}\right)^{3/2}\\&+\left(\varsigma K-\bar{\eta}\left(M_{an}-M+\varsigma Kc\frac{dM_{an}}{dH_e}\right)\right)\left(\frac{dM}{dH}\right)\\&-\left(M_{an}-M+\varsigma Kc\frac{dM_{an}}{dH_e}\right)=0\end{aligned}\tag{1}$$

$$\lambda=-\frac{\tilde{B}\Delta TM^2}{M_s^2}+\begin{cases}\dfrac{[1-\tanh(\sigma/\sigma_s)]\lambda_s}{M_s{}^2}M^2 & \sigma/\sigma_s\geq 0\\ \dfrac{[2-\tanh(2\sigma/\sigma_s)]\lambda_s}{2M_s{}^2}M^2 & \sigma/\sigma_s<0\end{cases}\tag{2}$$

In which:

$$\bar{\eta}=\eta-\frac{2\tilde{B}\Delta T\sigma}{\mu_0 M_s{}^2}+\begin{cases}\dfrac{2\sigma-2\sigma_s\ln[\cosh(\sigma/\sigma_s)]}{\mu_0 M_s{}^2}\lambda_s, & \sigma/\sigma_s\geq 0\\ \dfrac{4\sigma-\sigma_s\ln[\cosh(2\sigma/\sigma_s)]}{2\mu_0 M_s{}^2}\lambda_s, & \sigma/\sigma_s<0\end{cases}\tag{3}$$

$$M_{an}=M_s\frac{\left(1-\dfrac{\Delta T+T_r+273}{T_c+273}\right)^x}{\left(1-\dfrac{T_r+273}{T_c+273}\right)^x}\left(\coth\left(\frac{3\chi_m\left(1-\dfrac{T_r+273}{T_c+273}\right)^x}{M_s\left(1-\dfrac{\Delta T+T_r+273}{T_c+273}\right)^x}H_e\right)-\frac{M_s\left(1-\dfrac{\Delta T+T_r+273}{T_c+273}\right)^x}{3\chi_m H_e\left(1-\dfrac{T_r+273}{T_c+273}\right)^x}\right)\tag{4}$$

$$H_e=H+\eta M-\frac{2\tilde{B}\Delta T\sigma M}{\mu_0 M_s{}^2}+\begin{cases}\dfrac{2\sigma-2\sigma_s\ln[\cosh(\sigma/\sigma_s)]}{\mu_0 M_s{}^2}\lambda_s M, & \sigma/\sigma_s\geq 0\\ \dfrac{4\sigma-\sigma_s\ln[\cosh(2\sigma/\sigma_s)]}{2\mu_0 M_s{}^2}\lambda_s M, & \sigma/\sigma_s<0\end{cases}\tag{5}$$

And $\mu_0=4\pi\times 10^{-7}H/m$ is the vacuum permeability, d is diameter for Terfenol-D rod, ρ is the resistivity, $\tilde{\beta}=16$ and G = 0.1356 are a geometrical factor for cylinders and a dimensionless constant respectively, S is the cross-sectional area and V_0 is a parameter representing the internal potential experienced by domain walls, the parameter ς is taken +1 and −1 respectively when the intensity of the applied AC field increases and decreases, K is the pinning constant, c is the ratio of the initial normal magnetic susceptibility to the initial anhysteretic susceptibility. η is the Weiss molecular field coefficient, $\tilde{B}$ is equal to the slope of magnetostrictive strain versus increment temperature at the saturation magnetization, $\Delta T = T - T_r$ (where T is temperature and T_r is the spin reorientation temperature, T_c stands for the Curie temperature), χ_m is the magnetic susceptibility at the initial linear segments of magnetic curves. M_s, σ_s and λ_s are reference magnetization, stress and strain，respectively.

The domain flexing function is introduced as follows [16]:

$$c(H) = c_0 + e^{(|H|/H_{\max})-(1+\beta)} \tag{6}$$

In which, constant parameter c_0 is physically identical to the original parameter c. It describes the amount of the domain wall translation and bending with regard to the difference between the anhysteretic and irreversible magnetization. The exponential part with parameter β characterizes the amount of reversible relaxation of the domain wall bulged. The parameter β also depends on the maximum induction level. H represents a temporary value of the excitation magnetic field and $H_{\max}$ is its maximum value.

Now substituting (3)–(6) into (1) and then substituting the solved M into (2), the calculated magnetostriction λ can be obtained.

In order to identify the parameters, the follow optimization problem is constructed:

$$\begin{aligned} &\min \quad E(\boldsymbol{\theta}) = \sum_{k=1}^{Q}\left(\lambda(k) - \tilde{\lambda}(k)\right)^2 = \sum_{k=1}^{Q} e^2(k,\boldsymbol{\theta}) \\ &\text{s.t.} \quad d_r \le \theta_r \le b_r \qquad r = 1,2,... \end{aligned} \tag{7}$$

In which k is the kth sample time, Q is the number of all samples, $\tilde{\lambda}(k)$ is the experimental magnetostriction, $\lambda(k)$ is the calculated magnetostriction, $e(k,\boldsymbol{\theta}) = \lambda(k) - \tilde{\lambda}(k)$ is the magnetostriction error, θ_r is the rth element of the parameter $\boldsymbol{\theta}$, d_r and b_r are the lower and upper bounds on θ_r. Let $e(\boldsymbol{\theta}) = [e(1,\boldsymbol{\theta}) \;\; e(2,\boldsymbol{\theta}) \;\; ... \;\; e(Q,\boldsymbol{\theta})]$ be the magnetostriction error vector, the minimization problem (7) can be solved using the following immune clone algorithm.

3. Implementation of immune clone algorithm

As detailed in [13-14], immune clone algorithm can be used in optimization problem effectively. So here the minimization problem (7) is solved with it. The pseudocode is as follows:

Repeat:

a. Select a representative experimental magnetostriction $\tilde{\lambda}(k)$ (an antigen A) from a set of experimental data (population of antigens PA).
b. Take randomly R parameter vectors $\boldsymbol{\theta}$ (antibodies) from parameter space $\mathbf{d} \le \boldsymbol{\theta} \le \mathbf{b}$ (population of antibodies PS).
c. Substitute each parameter vector $\boldsymbol{\theta}$ (antibody) into the modified dynamical hysteresis model, then obtain the calculated magnetostriction $\lambda(k)$, match it against the selected experimental data $\tilde{\lambda}(k)$ (antigen A).
d. Find the parameter vector $\boldsymbol{\theta}$ (antibody) with the highest match score.
e. Add match score of winning parameter vector $\boldsymbol{\theta}$ (antibody) to its fitness.

Until the max number of cycles reached.

4. Identification results and discussions

First, in order to check the parameter identification program the dynamical magnetic-elastic-thermal coupled hysteresis model is reduced to a static form as follows [6]:

$$\left(\frac{dM}{dH}\right)=\frac{\left(M_{an}-M+\varsigma Kc\frac{dM_{an}}{dH_e}\right)}{\left(\varsigma K-\overline{\eta}\left(M_{an}-M+\varsigma Kc\frac{dM_{an}}{dH_e}\right)\right)} \tag{8}$$

$$\lambda=-\frac{\tilde{B}\Delta TM^2}{M_s^2}+\begin{cases}\dfrac{[1-\tanh(\sigma/\sigma_s)]\lambda_s}{M_s^{\,2}}M^2\\ \dfrac{[2-\tanh(2\sigma/\sigma_s)]\lambda_s}{2M_s^{\,2}}M^2\end{cases} \tag{9}$$

A hysteresis curve has been generated by the above form itself to check the agreement between the original and the fitted curve. The generated curve is considered to be the experimental curve and then the identification program is used to fit curve while the identified parameters is also obtained in the same procedure. Figure 1 shows the fitted results matched perfectly with the generated one. From table 1, one can see that the discrepancies between the original parameters and the estimated parameters are less than 5%. Figure 2 displays the convergence procedure of parameter identification. These results confirm us that the identification program proposed above is effective and successful.

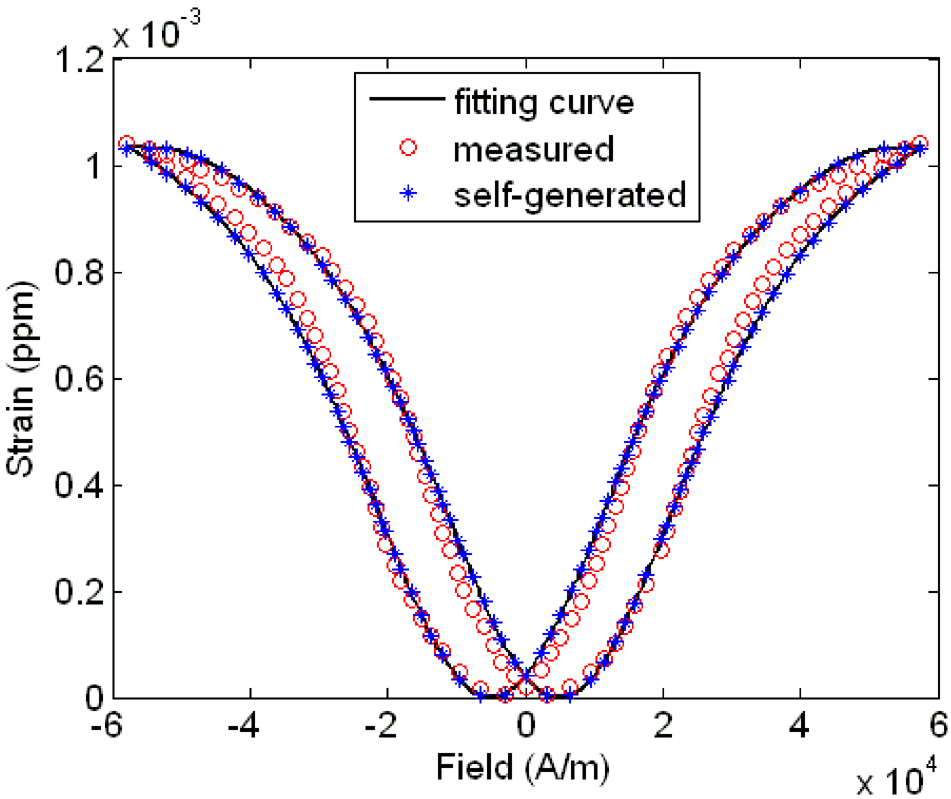

Figure 1 Fitting to the self-generated hysteresis loop of magnetic field versus strain relation.

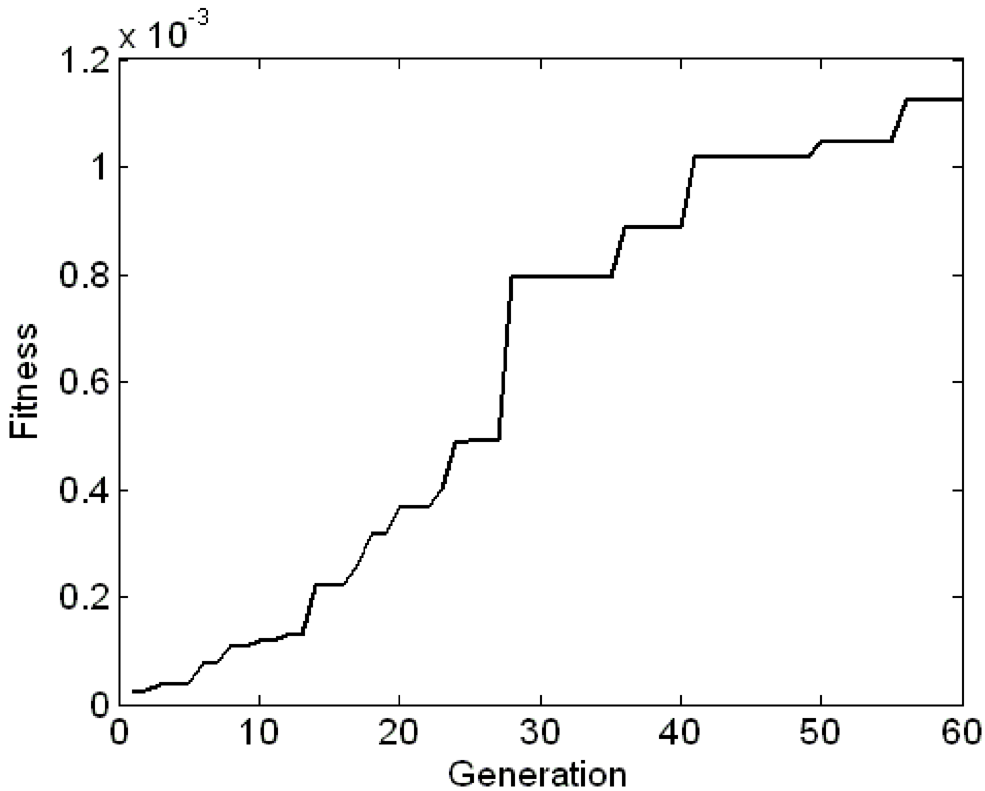

Figure 2 Fitness in the iteration procedure.

Table 1: The bounds for parameters, the parameters for self-generated curve, the estimation results and the estimation errors for parameters ($\mu_0 = 4\pi \times 10^{-7} H/m$)

Parameter	Parameter range	Original Parameter	Estimated parameter	Error (%)
K	$[3000.0\times\mu_0 ; 6000.0\times\mu_0]$	$5000.0\times\mu_0$	$4964.8\times\mu_0$	0.70
c	$[0.0000 ; 0.3000]$	0.1000	0.0956	4.40
M_s	$[0.6000/\mu_0 ; 1.5000/\mu_0]$	$0.9500/\mu_0$	$0.9493/\mu_0$	0.08
σ_s	$[150.00\times10^6 ; 250.00\times10^6]$	200.00×10^6	200.44×10^6	0.22
η	$[0.0100 ; 0.0300]$	0.02000	0.01995	0.25
χ_m	$[10.000 ; 50.000]$	35.000	35.103	0.29

Next, to overcome the unphysical phenomena of the minor loops encountered in previous models, the modified model and parameter identification program proposed in this paper are adopted. Figure 3 demonstrates the fitted results when the exciting frequency is 100Hz. It is clear to see that the unphysical tip of the minor loop is suppressed effectively. That means an optimal parameter vector for 100Hz is identified. Then the proposed parameter identification algorithm is adopted to predict the curve when exciting frequency is 500Hz. Figure 4 shows that the modified model does not give us the expected results when exciting frequency is 500Hz due to dynamical effect of the transducer under higher exciting frequency [12, 17-19].

Now the domain flexing function is considered more specifically. One can see clearly that an extra parameter β in the domain flexing function is introduced but do not give any explicit meaning of it. According to the above numerical results, perhaps the extra parameter is a function of the exciting frequency. A further step investigation of the extra parameter is lost in this paper, because of the limited experiment data.

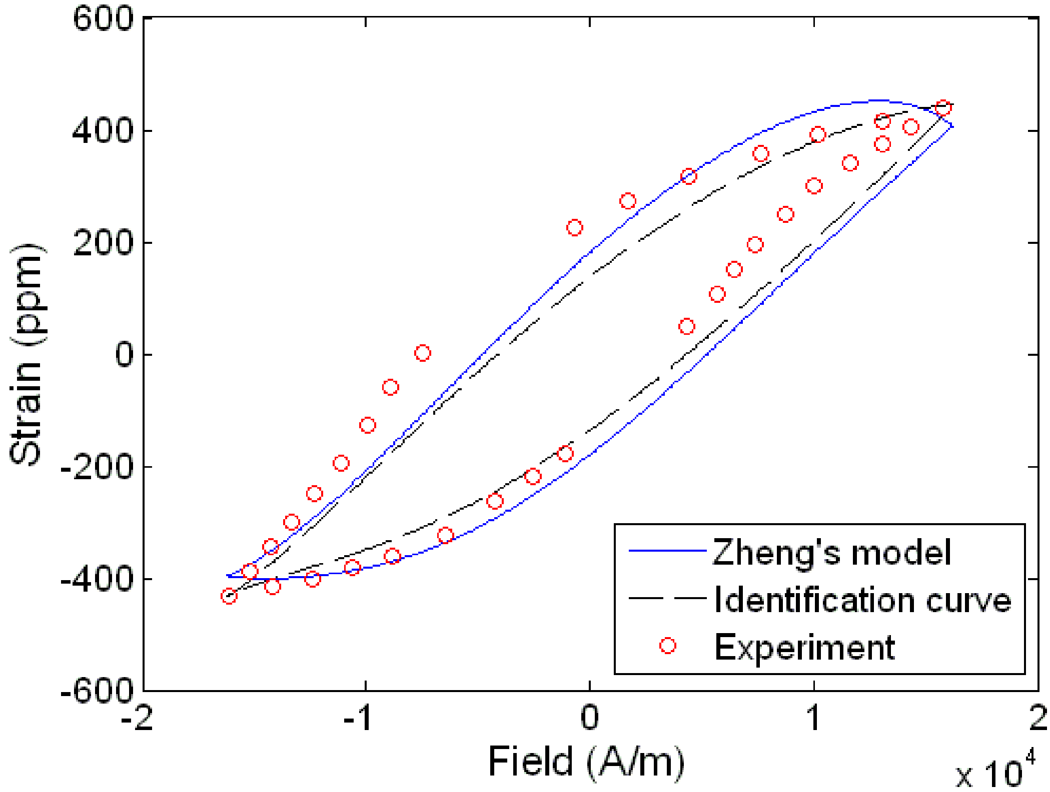

Figure.3. Fitted curve when exciting frequency is 100Hz.

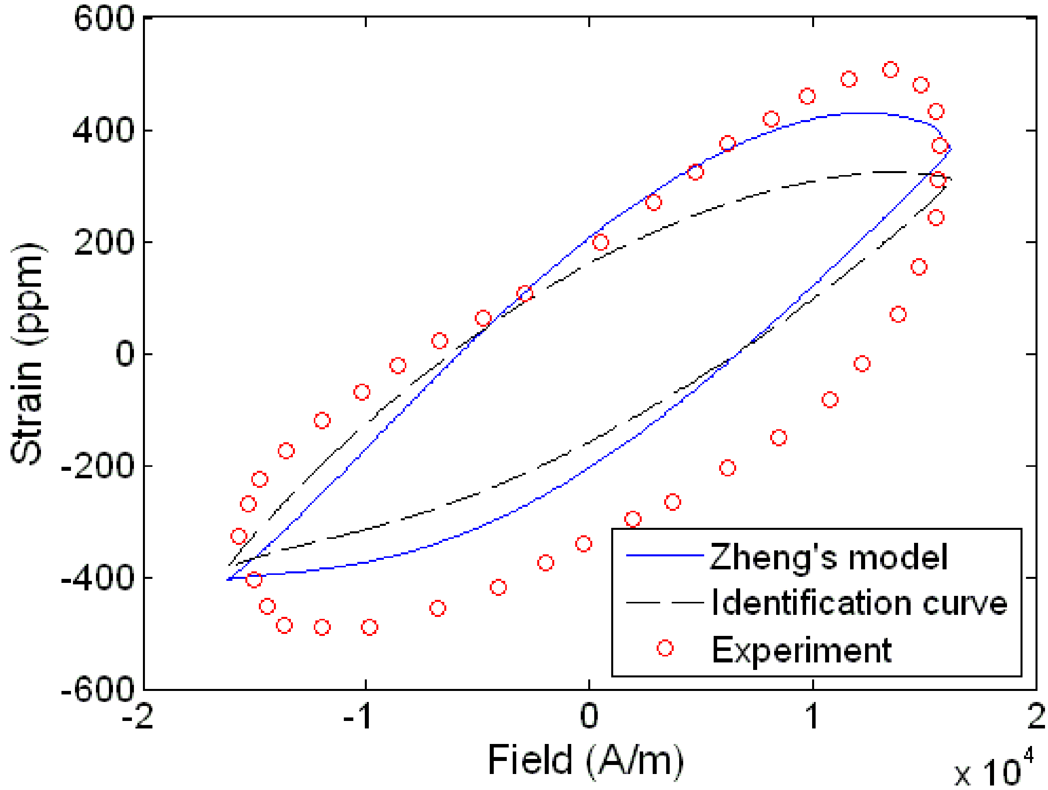

Figure.4. Fitted curve when exciting frequency is 500Hz.

5. Conclusions

The domain flexing function is introduced to the dynamical magnetic-elastic-thermal coupled hysteresis model to overcome the unphysical minor loop tip encountered in previous models. After doing so an immune clone algorithm is adopted to identify the model parameters. The results show that the modified model has effectively suppressed the unphysical phenomena appeared on the tips of minor loops when frequency of the exciting magnetic field is 100 Hz. But the extra parameter in domain flexing function has a great influence on the predicting results. A further investigation of this extra parameter will be included in the future investigation.

The parameter identification procedure based on the immune clone algorithm is performed successfully in above cases. The effectiveness of this procedure is proofed in Figure1 and Table1. Discrepancies between the identified parameters and the original chosen parameters are less than 5%.

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