Journal of Magnetism and Magnetic Materials 472 (2019) 59–65

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Research articles

A simple magnetization model for giant magnetostrictive actuator used on an electronic controlled injector

Yining Li[a], Peilin Zhang[a], Zhongbo He[a,*], Guangming Xue[a], Dinghai Wu[a], Sheng Li[b], Yudong Yang[c], Wei Zeng[d]

[a] Shijiazhuang Campus, Army Engineering University, Shijiazhuang 050003, China
[b] Armored Force Equipment and Technology Research Institute, Beijing 100072, China
[c] Ordnance NCO Academy, Wuhan 430075, China
[d] Special Operations Experiment Center, PLA Army Academy of Special Operations, Guilin 541000, China

ARTICLE INFO

Keywords:
Giant magnetostrictive actuator
Magnetization model
Jiles-Atherton model
Fitting model
Output displacement

ABSTRACT

Currently, most of the physics-based magnetization models for giant magnetostrictive actuator are complicated in their mathematical models. These complicated models pose considerable challenges for real-time control. Focus on the above issue, we proposed a fitting magnetization model using Arctangent function, as the inverse of the Arctangent function can solve it very quickly. This function was suitable to model the magnetic behavior of giant magnetostrictive actuator serving in an electronic controlled injector or other types of on-off valves. Applicable range of the model was determined through computing the maximum magnetic field. Then the deviations of the proposed fitting model and Jiles-Atherton model under different parameters were studied to verify the computing effects of the model. Then the effectiveness of the fitting model was verified by experimental results. With a high computing precision and a concise form, the proposed model shows great potentials for the real-time control of giant magnetostrictive actuators.

1. Introduction

The giant magnetostrictive material (GMM) is a type of functional material with magnetostrictive effect that magnetic energy and mechanical energy can be interconverted [1,2]. Compared with traditional magnetostrictive and piezoelectric actuators, the giant magnetostrictive actuator (GMA) using GMM has some advantages such as large magnetostriction [3], fast reaction [4], small hysteresis, high magnetic machine coupling coefficient and high Curie temperature etc. It has attracted attentions of many scholars and obtained widespread applications [5–9].

There is a hysteresis characteristic between the applied magnetic field and the magnetization of the GMM [10]. In order to improve the control precision and performance of the GMA, many scholars have established magnetization model to describe the hysteresis characteristics. These models can be mainly divided into phenomenon-based model [11–13] and physics-based model [14–17]. The physics-based models, including Stoner-Wolhfath model [18], Jiles-Atherton model [19,20] and Smith free-energy model [21], can describe the magnetizing process clearly and has been widely used in computing the magnetization within the GMM. This kind of model shows high computing accuracy and contains complex nonlinear equations which control strategies are difficult to execute.

Fig. 1 shows the influence of the GMM magnetization on the displacement of the GMA. The magnetization model contains hysteresis characteristics. When driving the high speed on-off valve, especially the electronic controlled injector, the GMA is driven under the square wave voltage (or its modification). In this case, the maximum and minimum magnetization determines the maximum and minimum displacement of GMA respectively. And the shape of the hysteresis curve corresponds to the displacement transient process.

Hysteresis curve is caused by the phase lag between the magnetization and magnetic field. In addition to the magnetization-magnetic field lag, there are coil current-voltage lag and displacement-strain lag when a GMA is delivering displacement. Considering the small hysteresis of GMM, the coil current-voltage lag and displacement-strain lag are quite higher than the magnetization-magnetic field lag. Magnetization-magnetic field hysteresis has little influence on the output of GMA. In addition, the transient process is so short that the change trend of the magnetization has really small influence on the displacement curve. The displacement curve changes little as long as the basic shape of the magnetization is remained in a reasonable range.

* Corresponding author.
E-mail address: hzb_hcl_xq@sina.com (Z. He).

https://doi.org/10.1016/j.jmmm.2018.09.126
Received 8 July 2018; Received in revised form 13 September 2018; Accepted 30 September 2018
Available online 04 October 2018

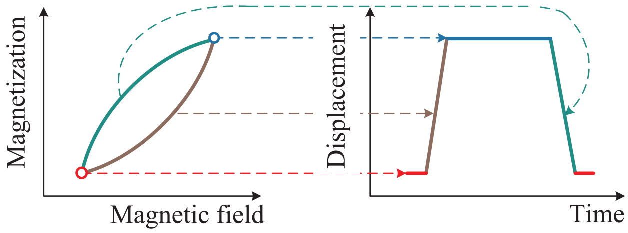

Fig. 1. Influence of the magnetization of GMM on the displacement of the GMA.

Considering the hysteresis model is the most nonlinear part of the whole output model of the GMA, it is not worth describing the hysteresis in a complex form because of its slight influence on the output. A simpler and more controlled magnetization model is more suitable for the GMA used on an electronic controlled injector.

Based on the traditional Jiles-Atherton (J-A) model, this paper established a fitting model to describe the magnetization. Neglecting hysteresis characteristics of the magnetization, we proposed magnetization model, calculated the amplitude accurately and described the change trend roughly. The computational deviations between proposed model and the J-A model were analyzed under different parameters. And the model was embedded into the GMA output model to examine its predicting effect on the GMA output. Computed and tested results showed similar calculating effects on computing magnetization between proposed model and J-A model. Proposed model was qualified for predicting the output displacement of GMA.

2. Static J-A model form and solution method

The irreversible magnetization process of ferromagnetic materials is the cause of hysteresis formation. And the J-A model is the most representative physical model describing the hysteresis characteristics. The J-A model is also widely used to describe the magnetic hysteresis of GMM. The static J-A model is very accurate in the case of inputting low frequency or square wave signals. In this model, the relationship between external magnetic field H and magnetization M is established by the following expression [22].

$$H_e = H + \alpha M \tag{1a}$$

$$M_{an} = M_s\left[\coth\left(\frac{H+\alpha M_{an}}{a}\right) - \frac{a}{H+\alpha M_{an}}\right] \tag{1b}$$

$$M = M_{irr} + M_{rev} \tag{1c}$$

$$M_{rev} = c(M_{an} - M_{irr}) \tag{1d}$$

$$\frac{dM_{irr}}{dH_e} = \delta_M \frac{M_{an}-M}{\delta k} \tag{1e}$$

where H_e is the effective magnetic field, M_{an} is anhysteretic magnetization, M_{rev} and M_{irr} are reversible and irreversible magnetization respectively, α is internal coupling parameter, M_s is saturation magnetization, c is reversible coefficient, a is anhysteretic shape coefficient, δ_M is used to guarantee positive incremental susceptibilities all the time, k is the irreversible loss coefficient and δ is sign parameter (equals to 1 when $dH/dt > 0$, equals to -1 when $dH/dt < 0$ and equals to 0 when $dH/dt = 0$, t is time). After some deductions, the relationship between H and M can be written as

$$\frac{dM}{dH} = \frac{\delta k c \frac{dM_{an}}{dH} + \delta_M(1-c)(M_{an}-M)}{\delta k - \alpha\delta_M(1-c)(M_{an}-M)} \tag{2}$$

Solve the M_{an} by the fixed point iteration method [3]

$$M_{an}^{i+1} = M_s\left[\coth\left(\frac{H+\alpha M_{an}^{i}}{a}\right) - \frac{a}{H+\alpha M_{an}^{i}}\right] \tag{3}$$

where the superscript i is the iterative number and M_{an}^{i+1} is the M_{an} value after $i+1$ iterative numbers.

Then M can be solved using the 4th order Runge-Kutta method

$$M_{n+1} = M_n + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4) \tag{4a}$$

$$k_1 = \varphi(H_n, M_n) \tag{4b}$$

$$k_2 = \varphi\left(H_n + \frac{h}{2}, M_n + \frac{1}{2}hk_1\right) \tag{4c}$$

$$k_3 = \varphi\left(H_n + \frac{h}{2}, M_n + \frac{1}{2}hk_2\right) \tag{4d}$$

$$k_4 = \varphi(H_n + h, M_n + hk_3) \tag{4e}$$

$$\varphi(H, M) = \frac{\delta k c \frac{dM_{an}}{dH} + (1-c)(M_{an}-M)}{\delta k - \alpha(1-c)(M_{an}-M)} \tag{4f}$$

where h is the computing step-size, M_n and H_n are the values of M and H at the n steps of computing. M_{n+1} is the values of M at the $n+1$ steps of computing.

Due to the complex expression of J-A model, the computing time is really long. And the model is difficult to be controlled as the inverse model is unsolved.

3. Simple magnetization model

3.1. Expression of the magnetization model

Considering the influence of the hysteresis on the GMA output, which has been analyzed in Section 1, it seems not so necessary to employ complex J-A model to describe the magnetization within the GMM. To compute and control more easily, a simpler magnetization model is more suitable. In this simpler model, the important information like the amplitude and change rule of the magnetization-magnetic field curve should be remained approximately while the hysteresis characteristic can be removed. When the residual displacement caused by the minimum magnetization of the GMA is so small that it causes unstable close of the injector, the minimum magnetization has no influences on the working process of the giant magnetostrictive injector.

Neglecting the hysteresis, one simple idea is taking anhysteretic magnetization M_{an} as the total magnetization M. The expression of M_{an} shown in Eq. (1b) is complicated. It is given using an implicit form of Langevin function with intermittent points and the inverse function can't be solved analytically. We hope to find a simpler and explicit function with easily solved inverse function to replace the Langevin form of M_{an}.

With similar change trend to the Langevin function and simple format, the Arctangent function can be introduced to describe the anhysteretic magnetization M_{an} and then fit the total magnetization M. In order to make the Arctangent function and the Langevin function fit better, the X-axis compression coefficient of 1.93 and the Y-axis compression coefficient of $2/\pi$ should be added firstly. The curves of $y = 2/\pi(\arctan(x/1.93))$, $y = \coth(x) - 1/x$ and $y = \arctan(x)$ are shown in Fig. 2. From Fig. 2, the curve of the Arctangent function with two compression coefficients is quite consistent with the curve of the Langevin function.

In Eq. (1b), the independent variable is $(H + \alpha M_{an})/a$ and the equation is implicit because both sides of the equation contain the dependent variable M_{an}. In order to simplify the computations, a simple idea is that M_{an} in the right side can be replaced directly by a linear function of H. The feasibility of this idea can be verified by the following contents.

Therefore, the fitting model of magnetization M is defined as