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Research Article

Research of Jiles-Atherton Dynamic Model in Giant Magnetostrictive Actuator

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Due to the existence of multicoupled nonlinear factors in the giant magnetostrictive actuator (GMA), building precise mathematical model is highly important to study GMA's characteristics and control strategies. Minor hysteresis loops near the bias magnetic field would be often applied because of its relatively good linearity. Load, friction, and disc spring stiffness seriously affect the output characteristics of the GMA in high frequency. Therefore, the current-displacement dynamic minor loops mathematical model coupling of electric-magnetic-machine is established according to Jiles-Atherton (J-A) dynamic model of hysteresis material, GMA structural dynamic equation, Ampere loop circuit law, and nonlinear piezomagnetic equation and demonstrates its correctness and effectiveness in the experiments. Finally, some laws are achieved between key structural parameters and output characteristics of GMA, which provides important theoretical foundation for structural design.

1. Introduction

Giant magnetostrictive materials (GMM) are widely used in transducer, precision actuator, and active vibration [1–3] because of large magnetostrictive coefficient, excellent dynamic characteristic, and high energy density. When they are applied in high frequency, establishing accurate mathematical model is crucial to improving controllability and stability [4, 5]. J-A model is established based on magnetization principle by Jiles and Atherton, which has a wide application and fast development because of clear physical conception, high stability, and accuracy [6–9]. In recent years, many experts established the mathematical models of hysteresis materials including frequency, pressure, temperature, and other sensitive factors based on the J-A model that had developed a relatively mature modeling theory [10–13]. However, these modes of GMA are mainly studied from material and ignore the structural factors such as load, disc spring stiffness, and friction which have a strong impact on output characteristics especially in high frequency. Therefore, a new dynamic model including load, disc spring stiffness, and friction is established based on combination of minor loops J-A model of GMM, structural dynamic equation of GMA, Ampere circuit law, and nonlinear piezomagnetic equation through analyzing the working principle of GMA. Then, the correctness and validity of this model are proved by experiments in different conditions. Finally, some output characteristics laws are revealed by analyzing key structural parameters.

2. Working Principle of GMA

The GMM rod drives load under the action of the magnetic field generated by the excitation coil and permanent magnet (Figure 1). The magnetostrictive coefficient of GMM is raised by prepressure which is generated by compressing disc spring. Bias magnetic fields are produced by permanent magnets. On the one hand, the double frequency characteristic of GMM could be removed; on the other hand, the high linearity part of hysteresis loop near the bias magnetic fields is applied to reduce the nonlinearity. The temperature control system provides relatively constant temperature environment for the GMM rod.

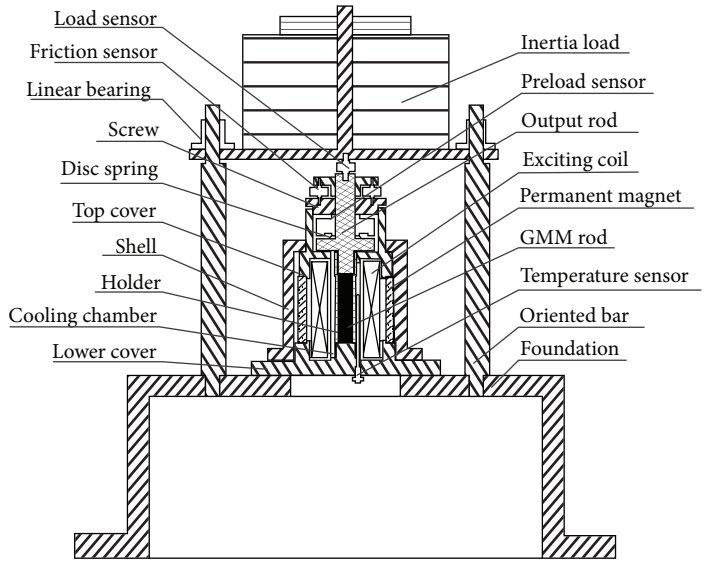


Figure 1: Structure of GMA.

3. Jiles-Atherton Dynamic Model

The J-A model is developed taking into account the phenomenology of domain wall translation through the so-called pinning center, which might be nonmagnetic inclusions and impurities, grain boundaries, voids, and so forth, causing residual stress that hinders the magnetization process [14]. The motion of magnetic domains can be divided into reversible or irreversible movement and rotation. Thus, according to model developers, total magnetization M can be divided into reversible and irreversible terms [6]. Hence,

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

where M_{rev} is reversible magnetization and M_{irr} is irreversible magnetization. Consider

$$\begin{aligned} M_{\text{rev}} &= c\left(M_{\text{an}} - M_{\text{irr}}\right), \\ M_{\text{irr}} &= \frac{\left(M - cM_{\text{an}}\right)}{(1-c)}, \end{aligned} \tag{2}$$

where c is reversible loss coefficient.

The modified Langevin equation is used to fit the isotropic material and anhysteretic magnetization M_{an} is obtained in

$$M_{\text{an}} = M_s\left(\coth\frac{H + \alpha M_{\text{an}}}{a} - \frac{a}{H + \alpha M_{\text{an}}}\right), \tag{3}$$

where M_s is saturation magnetization, a is shape parameter of the anhysteretic magnetization, α is internal coupling field coefficient among different magnetic domains, and H is magnetic strength.

Equation (4), which takes into account dynamic effects due to eddy currents in the material, is derived by introducing additional energy term in the basic J-A equation [15]. Hence,

$$\begin{aligned} M = M_{\text{an}} &- k\delta(1-c)\frac{\mathrm{d}M_{\text{irr}}}{\mathrm{d}H_e} - k_1\frac{\mathrm{d}M}{\mathrm{d}t}\frac{\mathrm{d}M}{\mathrm{d}H_e} \\ &- k_2\left|\frac{\mathrm{d}M}{\mathrm{d}t}\right|^{1/2}\frac{\mathrm{d}M}{\mathrm{d}H_e}, \end{aligned} \tag{4}$$

where k_1 is eddy-current loss factor, k_2 is anomalous loss factor, k is irreversible loss coefficient, H_e is effective magnetic field strength, and δ is direction coefficient, when $\mathrm{d}H/\mathrm{d}t > 0$, $\delta = 1$ and when $\mathrm{d}H/\mathrm{d}t < 0$, $\delta = -1$.

Stress can change certain features of some magnetic domains to influence H_e. When the stress is σ, the effective magnetic field H_e becomes formula (5) and parameter α is modified to be $\tilde{\alpha}$ [16, 17]. Hence,

$$H_e = H + \alpha M + \frac{9\lambda_s\sigma}{2\mu_0 M_s^2}M = H + \tilde{\alpha}M, \tag{5}$$

$$\tilde{\alpha} = \alpha + \frac{9\lambda_s\sigma}{2\mu_0 M_s^2}, \tag{6}$$

where λ_s is saturation magnetostrictive coefficient.

According to parameters characteristics of J-A model and the difference between simulation and experiment, the minor loop J-A model can be got through modifying the parameters a, α, c, and k [18]. Hence,

$$\begin{aligned} a_{\text{minor}} &= ae^{\gamma_a(\lambda_s - \lambda_m)}, \\ \alpha_{\text{minor}} &= \alpha e^{\gamma_\alpha(\lambda_s - \lambda_m)}, \\ c_{\text{minor}} &= ce^{\gamma_c(\lambda_s - \lambda_m)}, \\ k_{\text{minor}} &= ke^{\gamma_k(\lambda_s - \lambda_m)}, \end{aligned} \tag{7}$$

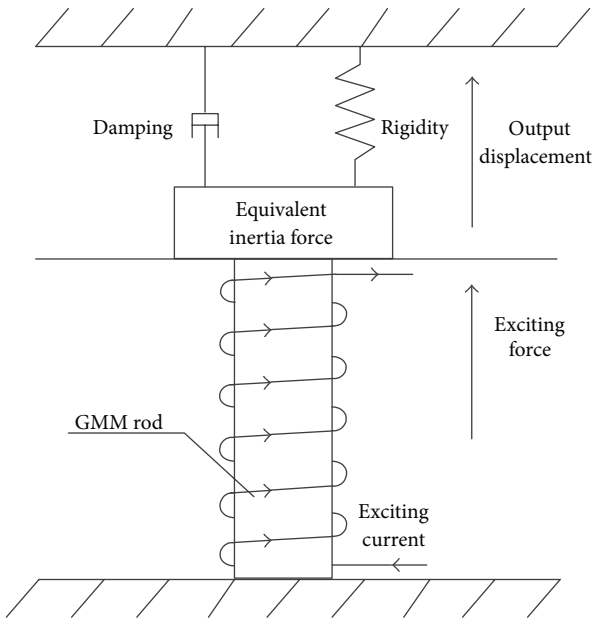


Figure 2: Equivalent mechanical mode.

where γ_k, γ_a, γ_c, and γ_α are, respectively, modified coefficient of k, a, c, and α; λ_m is the maximum magnetostriction coefficient of minor loop.

We can get dynamic minor loop J-A model of GMM according to formulas (1)–(7).

4. Structural Dynamics Model

GMA can be considered as a single degree of freedom mass-spring-damping system. GMM rod drives the load under the action of magnetic field. In this section, the dynamic mathematical model of GMA is established considering structural characteristics such as load, disc spring, and friction and the following assumptions should be accepted:

(1) GMM rod should be in uniform magnetic field.

(2) The working temperature is 293 K and remains constant all the time.

(3) The output displacement is 0 when bias magnetic field is 22.5 kA/m, and prepressure is 6 Mpa.

(4) The output displacement of one end is 0, while the other end keeps the same output characteristics with load such as displacement, velocity, and acceleration.

(5) The output displacement x of GMM rod is equal to εL and the output force F is equal to $-\sigma A$.

Based on the above assumptions, the equivalent mechanical mode can be obtained according to the working principle of GMA (Figure 2). According to Newton's second law, the output force F of GMA is

$$\begin{aligned} F &= -\sigma A = M_e \ddot{x} + C_M \dot{x} + F_f + F_d, \\ M_e &= \frac{M_M}{3} + M_L, \end{aligned} \tag{8}$$

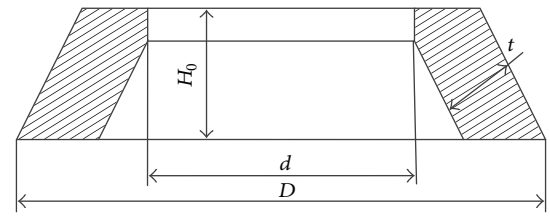


Figure 3: Structural parameters of disc spring.

where M_e is equivalent mass, C_M is the impedance factor of GMA, F_f is friction, F_d is the pressure of disc spring, M_M is the quality of GMM bar that is equal to 1/3 of itself according to kinetic energy Lagrange function [19], and M_L is mass of the load.

4.1. The Output Force of GMM Rod. When the magnetic field intensity is relatively large, the magnetization process in the material will produce serious hysteresis nonlinearity. The quadratic magnetic domain rotation model is introduced into the linear piezomagnetic equation [20]. Hence,

$$\varepsilon = \frac{\sigma}{E} + \gamma_1 M^2, \tag{9}$$

where γ_1 is the magnetic elastic coefficient of GMM rod and E is the elasticity modulus of GMM rod.

4.2. Pressure of Disc Spring. The pressure generated by a single disc spring [21] is given by

$$\begin{aligned} F_d = \frac{(x + x_0)\, t^3}{\chi D^2} \left[\left(\frac{h_0}{t} - \frac{(x + x_0)}{t} \right) \right. \\ \left. \cdot \left(\frac{h_0}{t} - \frac{(x + x_0)}{2t} \right) + 1 \right] - \sigma_0 A, \end{aligned} \tag{10}$$

where σ_0 is the prestress, x_0 is the predisplacement in the prestress, χ is shape factor of disc spring, and h_0 is its maximum deformation. The geometric parameters are shown in Figure 3.

4.3. Friction. According to principle and characteristics of friction and working environment of GMA, Coulomb + Viscosity friction model (Figure 4) is selected [22].

Friction model is shown in

$$F_f = f_c v + f_{\max} \operatorname{sgn}(v), \tag{11}$$

where $f_{\max}$ is the maximum static friction, f_c is the Coulomb friction coefficient, and v is velocity of the GMM rod.

4.4. Ampere Circuital Theorem. According to Ampere circuital theorem considering leakage in magnetic circuit [23], the magnetic field strength H is

$$H = H_{\text{bias}} + k_{\text{coil}} I, \tag{12}$$

where H_{bias} is the bias magnetic field strength and k_{coil} is exciting coefficient of the coil.

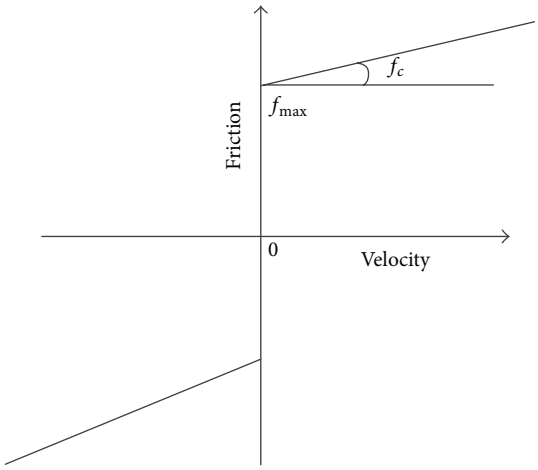


Figure 4: Friction model.

Table 1: Model parameters.

Parameter	Value
M_s	380769 A/m
k	22643 A/m
C_M	3.02×10^4 Ns/m
λ_s	1500 ppm
γ_1	1.07×10^{-14} A^2/m^2
a	47704 A/m
c	0.1
k_1	2.62×10^{-5}
γ_a	−10
γ_k	−30
α	0.417
k_{coil}	16492 m^{-1}
k_2	0.312
γ_α	10
γ_c	1500

The current-displacement mathematical model of GMA could be obtained by connecting formulas (1)–(7) with (9)–(12) and its parameters (Table 1) are identified by adopting modified simulated annealing differential evolution algorithm which has a high convergence speed and accuracy.

5. Test Verification

GMA testbed is mainly composed of GMA, laser displacement sensor, and temperature control system (Figure 5). The measurement and control system applies RTX as lower computer system software and LabWindows as upper computer system software and sampling period is 0.5 ms. The temperature sensor is installed near GMM rod (Figure 1) and temperature control system can pass heat through circulating water which can be controlled within 1 K by heater and cooler. The V100-MS laser displacement sensor can measure the displacement, velocity, and acceleration and its displacement measurement accuracy is up to 5 μm/V. The ISF20DA250 servo driver can provide exciting current with feedback control and its frequency response is up to 15 kHz (see Figure 6). The simulation and experiment curves in different conditions are shown in Figure 7, which prove the validity and accuracy of this mathematical model.

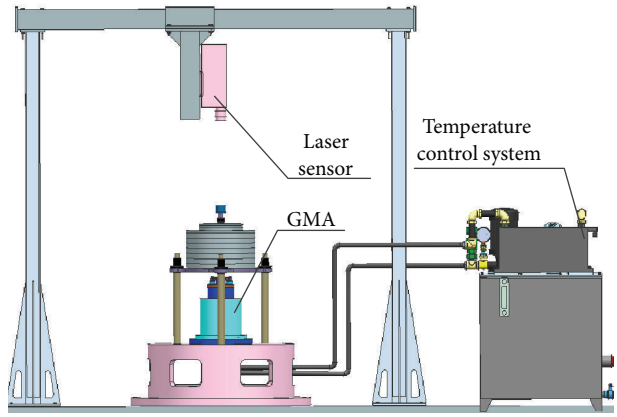


Figure 5: GMA testbed.

Table 2: Structural parameters of disc spring.

	D (mm)	d (mm)	t (mm)	h_0 (mm)
A	63	31	3.5	1.4
B	63	31	2.5	1.75
C	63	31	1.8	2.35

6. Studies on Key Parameters of the Model

In this section, the output characteristics laws of GMA are revealed by studying structural parameters such as disc spring stiffness and friction.

6.1. Studies on Characteristics of Disc Spring. The disc spring, a key part that provides prepressure, has a serious impact on output characteristics of GMA because of its nonlinearity. This paper studies three series of disc springs (A, B, and C) whose inner and outer diameter are the same and their structural parameters and mechanical property are shown in Table 2 and Figure 8. Figure 9 shows the output displacement of GMA under 20 Hz. After analyzing Figures 8 and 9, we can conclude that the larger stiffness of disc spring can reduce magnetostriction coefficient.

6.2. Studies on Friction. This section mainly studies Coulomb friction coefficient f_c and the maximum static friction $f_{\max}$ in friction model. When f_c takes 10 Nm/s and 100 Nm/s, respectively, the output displacement of GMA under 20 Hz is shown in Figure 10. The larger the f_c, the more serious the hysteresis energy loss. As a result, the Coulomb friction coefficient should be as small as possible.

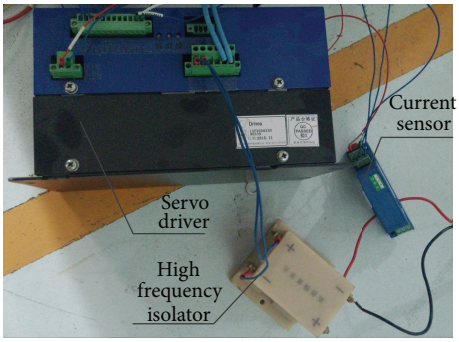
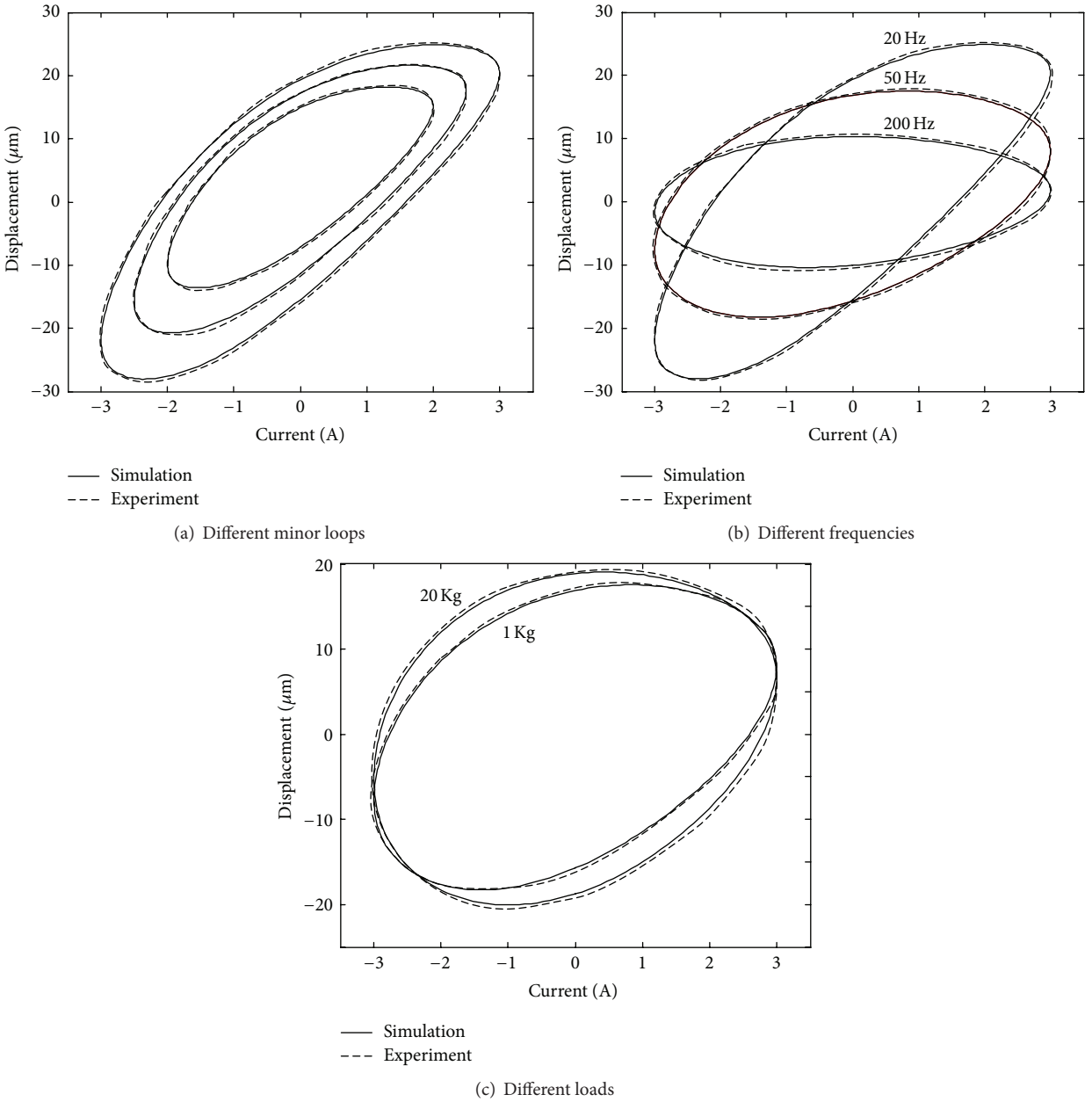


Figure 6: Servo driver.



(a) Different minor loops

(b) Different frequencies

(c) Different loads

Figure 7: Experiment and simulation.

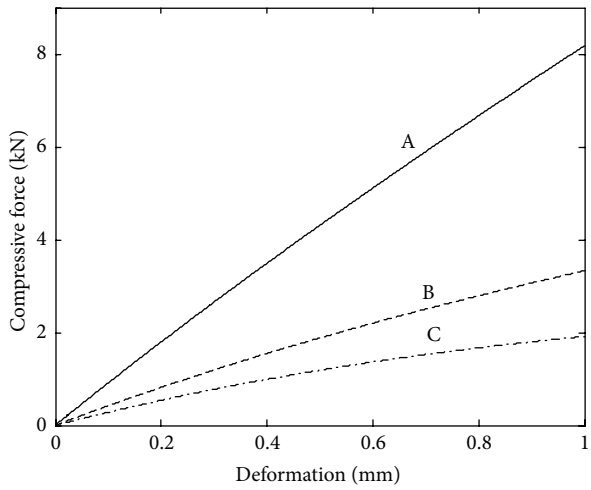


Figure 8: Mechanical characteristics curve.

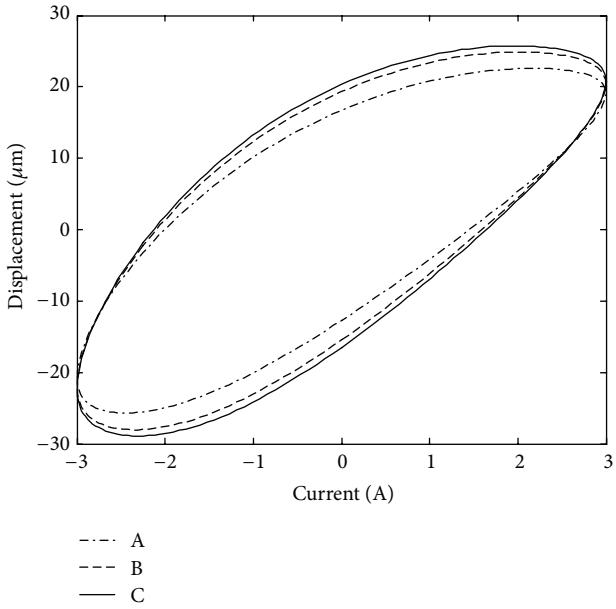


Figure 9: Hysteresis loop about springs.

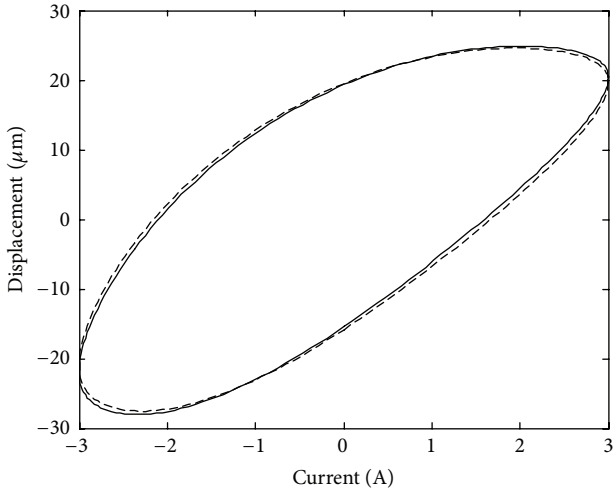


Figure 10: Hysteresis loop about f_c.

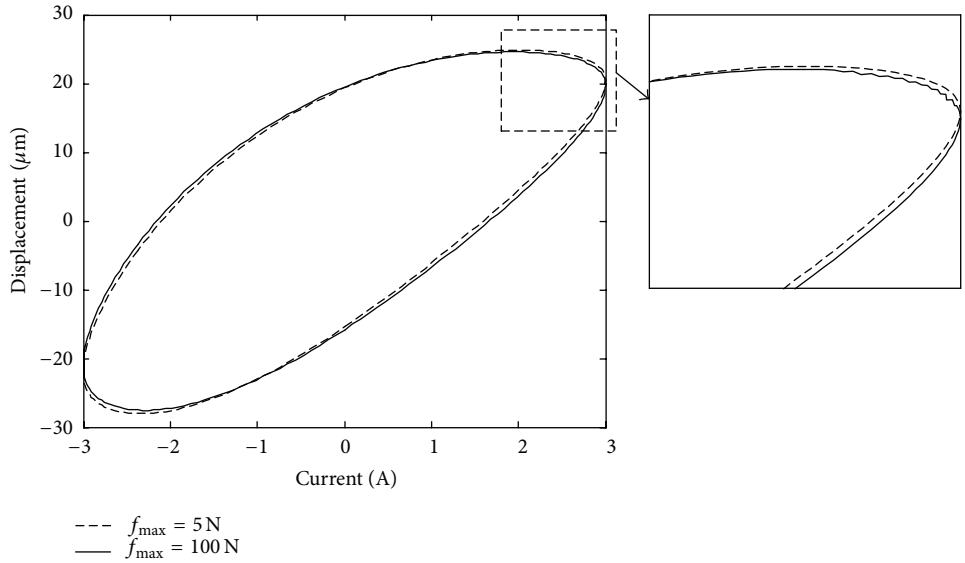


Figure 11: Hysteresis loop about f_{max}.

When f_{max} takes 5 N and 100 N, the output displacement of GMA in 20 Hz is shown in Figure 11. With the increasing of f_{max}, serious low speed crawling and buffeting will appear in the end of hysteresis loop. Therefore, f_{max} should be as small as possible.

7. Conclusion

(1) Structural parameters have a strong impact on output characteristics of GMA in high frequency.

(2) The dynamic mathematical model of GMA including structural element such as load, disc spring, and friction has a great adaptability and accuracy.

(3) The stiffness of disc spring influences the output characteristics of GMA.

(4) Friction affects unfavourably the output characteristics.

Competing Interests

The authors declare that they have no competing interests.

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