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Research on hysteresis loop considering the prestress effect and electrical input dynamics for a giant magnetostrictive actuator

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Abstract

In this paper, focusing on the application-oriented giant magnetostrictive material (GMM)-based electro-hydrostatic actuator, which features an applied magnetic field at high frequency and high amplitude, and concentrating on the static and dynamic characteristics of a giant magnetostrictive actuator (GMA) considering the prestress effect on the GMM rod and the electrical input dynamics involving the power amplifier and the inductive coil, a methodology for studying the static and dynamic characteristics of a GMA using the hysteresis loop as a tool is developed. A GMA that can display the preforce on the GMM rod in real-time is designed, and a magnetostrictive model dependent on the prestress on a GMM rod instead of the existing quadratic domain rotation model is proposed. Additionally, an electrical input dynamics model to excite GMA is developed according to the simplified circuit diagram, and the corresponding parameters are identified by the experimental data. A dynamic magnetization model with the eddy current effect is deduced according to the Jiles–Atherton model and the Maxwell equations. Next, all of the parameters, including the electrical input characteristics, the dynamic magnetization and the mechanical structure of GMA, are identified by the experimental data from the current response, magnetization response and displacement response, respectively. Finally, a comprehensive comparison between the model results and experimental data is performed, and the results show that the test data agree well with the presented model results. An analysis on the relation between the GMA displacement response and the parameters from the electrical input dynamics, magnetization dynamics and mechanical structural dynamics is performed.

Keywords: giant magnetostrictive actuator, prestress, eddy current, dynamics, hysteresis

(Some figures may appear in colour only in the online journal)

1. Introduction

A typical representative of giant magnetostrictive materials (GMMs) is Terfenol-D, a metal alloy comprising terbium, dysprosium and iron, which can produce ‘giant’ magnetostriction under an applied magnetic field. The maximum strain can reach 2000 ppm, which is much higher than any other traditional magnetostrictive material, such as nickel, iron and cobalt. In addition, GMMs feature high force, wide bandwidth, unlimited cycle life, wide temperature range and microsecond response time [1–3]. Therefore, GMMs have significant roles in commercial products and military applications, such as sonar, micro-positioning devices, robots, motors, servovalves and vibration control. However, the
relatively small displacement of a giant magnetostrictive actuator (GMA) is a limit for some applications, such as aviation and space. One promising scheme to extend GMMs applications in the aerospace field, called the smart-material-based electro-hydrostatic actuator (SMEHA), which uses frequency rectification to transform small-amplitude and high-frequency oscillation movement of smart materials into large-amplitude and unidirectional or bidirectional continuous movement of a hydraulic cylinder [4–7], is a good candidate to overcome the restriction. For SMEHA, a large power-to-weight ratio is an important focus of research and can be obtained by high-frequency and high-amplitude magnetic field excitement. One of the challenges is that an accurate GMA model under the excitation conditions is difficult to obtain because the characteristics of multi-field coupling [8, 9] and multivariate dependence [10, 11], for instance, the electrical input dynamics, hysteresis, eddy current effect, prestress effect, permeability and Young modulus variation of the GMM rod. Because GMM strain depends on the applied magnetic field and the prestress on the GMM rod, which typically varies when the applied magnetic field is an alternating magnetic field, the GMM static strain exhibits a nonlinear relation with the excited magnetic field amplitude. The GMM dynamic strain also depends on multi-factors, such as electrical dynamics, eddy current effect and mechanical structural dynamics, which would present a more complicated situation with increasing excitation frequency of the applied magnetic field. These inherent properties and drawbacks make the effective use of GMMs challenging. An accurate dynamic model meeting the high-field and high-frequency demands is important to develop GMMs for more extensive applications.

The existing models can be divided into two groups: micromechanics models or physics-based models, which are molecular level models, a typical representative of which is the Jiles–Atherton model [12, 13], which gives a quantitative description the nonlinear hysteresis relationship between the input magnetic field and the magnetization of the GMM rod based on magnetic domain theory. The Jiles–Atherton model is further extended to include the stress effects [14, 15]; the other is micromechanics models or phenomenological models, which provide mathematical expressions to describe the nonlinear hysteresis relationship between the input magnetic field and the magnetization of the GMM rod based on experimental data. An earlier phenomenological hysteresis model is the Preisach model [16–18], which can be specified solely in terms of mathematical criteria and can be employed to characterize hysteresis for GMMs. However, the Preisach model also has a number of limitations: due to the assumption that hysteresis is rate-independent in the Preisach model, it is difficult to quantify the frequency or rate-dependence in GMMs hysteresis. Moreover, the discontinuous relay operators in the Preisach model also limit its application; thus, another popular phenomenological hysteresis model, called the Prandtl–Ishlinskii model [19], was developed using continuous play or stop hysteresis operators to facilitate the formulation of the inverse rate-dependent hysteresis model, which can contribute to real-time control and compensation of GMA hysteresis.

The above-mentioned models focused on the magnetization process of GMA; however, a complete dynamic model of GMA also includes the electrical input dynamics and the mechanical structural dynamics. The electrical input dynamics convert input voltage into current or applied magnetic field. The mechanical structural dynamics implement magnetic–mechanical conversion from magnetization to displacement of the GMA.

Fewer electrical input dynamics models have been developed to depict the dynamic voltage–current (or voltage–magnetic field) conversion behavior, such as a first-order inertia object with dead time [20] and a second-order oscillating element [21]. The former have added the nonlinearity factor and the latter have ignored some elements, such as the compensation capacitor element.

The mechanical structural dynamics model generally consist of a quadratic domain rotation model [22] and a single degree-of-freedom (SDOF) vibration model [23]. Prestress on the GMM rod has been verified to have a significant impact on the output force and the output displacement of the GMA [24]. Pei [25] presented an energy distribution parameter related to the prestress on the GMM rod and temperature to estimate the prestress effects on magnetization. The results show that magnetization decreases with an increase of the prestress on the GMM rod. Based on the Preisach model, Davino [26] proposed a model using a memoryless effective current function from the Preisach algorithm to describe magnetostriiction with variation of the applied mechanical load.

In conclusion, although GMMs have been widely used in many fields, some intrinsic properties of these materials, such as the characteristics of multi-field coupling, featured electric–magnetic–mechanical coupling and multivariate dependence characterizing the magnetic field and the prestress dependence, make their application challenging. Every dynamic process has an effect on the dynamic characteristics of GMA; however, the existing models of GMA are highly focused on the magnetization hysteresis model, which describes the hysteresis relation between the input magnetic field and the magnetization of GMMs. In contrast, the electrical input dynamics and the eddy current effect on GMM magnetization have received less focus in the existing models [14, 24–26, 30, 31]. The existing models mostly concentrate an applied magnetic field of less than 60 KA m$^{-1}$ [14, 23, 24, 30, 31] and an excitation frequency 800 Hz [23, 27–29, 32]. However, under an applied magnetic field with high frequency and high amplitude, it is more important to determine to what extent each dynamic process exerts influence on the output displacement dynamic behavior of the GMA.

In this paper, with the aim to determine the application requirements for SMEHA, an electrical input dynamics model, magnetization dynamics model and mechanical structural dynamics model are built under the driving magnetic field from 0 to 100 KA m$^{-1}$ (0–8 A) and a driving frequency from 0 to 1000 Hz. Methodology using the hysteresis
loop as a tool is developed to study the dynamic performance of GMA by analyzing the hysteresis loop shape.

The presented model prediction results agree perfectly with experiment results, not only under quasi-static operating conditions (an applied magnetic field of 0–8 A and an excitation frequency under 20 Hz) but also under dynamic operating conditions (an excitation frequency under 1000 Hz). Furthermore, the model in this paper has desirable characteristics, such as being computationally simple and efficient and having reasonably easy to determine parameters. Therefore, the research in this paper provides a basic theoretical model for accurate characterization of the GMA, which can be used in SMEHAs that are typically excited by an applied magnetic field with high frequency and high amplitude.

2. Actuator configuration and operation process

Figure 1 illustrates the configuration of GMA, which mainly consists of a GMM rod (a Terfonel-D rod is used in this study), a displacement output rod, a disc spring, a force output rod and a force sensor.

The spring applies a preforce on the GMM rod, which can be detected by force sensor. The operation process of GMA is as follows, firstly, the coil is excited by direct current to provide a bias magnetic field, then, a AC driving current energizes the coil to produce a driving magnetic field. When the sign of the driving magnetic field is the same as the sign of the bias magnetic field, the GMM rod elongates; conversely, the GMM rod shortens. The preforce on GMM rod can be captured and displayed in real time by the force sensor.

3. Dynamic model

Based on the above operation process, in response to an input voltage signal, GMA performs a multi-physics field dynamic conversion, including the electrical input dynamics, magnetization dynamics and mechanical strain dynamics, which can be shown in figure 2.

3.1. Electrical input dynamics model

The electrical input dynamics model describes the quantification relationship between the input voltage and the output current or the applied magnetic field, which involves the power amplifier dynamics and the inductive winding coil dynamics. The power amplifier in this study is operated in the controlled current mode by an RC network. If the load’s impedance changes, the amplifier will seek to maintain this transconductance (ratio of input voltage to output current) by
increasing or decreasing the voltage it produces to provide an output current that is proportional to the input voltage. The electrical input dynamics can be simplified as shown in figure 3.

As shown in figure 3, \( L_d \) and \( R_d \) are inductance and resistance in the driving coil, \( C_c \) and \( R_c \) are the compensating capacitance and compensating resistance in the power amplifier, \( R_s \) is the sampling resistance, and \( R_1, R_2, R_3, R_4 \) are the precise divider resistances.

Based on the properties of the operational amplifier: \( \frac{U_i}{U_i} \), thus

\[
\frac{R_3}{R_3 + R_3} U_i = \frac{R_2}{R_2 + R_4} U_i.
\]

Based on Kirchhoff’s law

\[
I_d = \frac{Z_c}{Z_c + Z_d} \cdot \frac{R_3}{R_3 + R_3} \cdot \frac{R_2}{R_2 + R_4} \cdot \frac{1}{R_4} U_i.
\]

Substitute equations (2) to (1)

\[
I_d = \frac{Z_c}{Z_c + Z_d} \cdot \frac{R_3}{R_3 + R_3} \cdot \frac{R_2}{R_2 + R_4} \cdot \frac{1}{R_4} U_i.
\]

Substitute \( Z_c = \frac{1}{\sqrt{L_c} + R_c} \), \( Z_d = \frac{1}{\sqrt{L_d} + R_d} \) into equation (3)

\[
I_d = \frac{1 + j\omega C_c R_c}{C_c L_d (j\omega)^2 + C_c (R_c + R_d) j\omega + 1}
\times \frac{R_3}{R_3 + R_3} \cdot \frac{R_2}{R_2 + R_4} \cdot \frac{1}{R_4} U_i.
\]

The transfer function from \( U_i \) to \( I_d \) can be written as

\[
G(s) = \frac{I_d(s)}{U_i(s)} = \frac{1 + C_c R_c s}{C_c L_d s^2 + C_c (R_c + R_d) s + 1}
\times \frac{R_3}{R_3 + R_3} \cdot \frac{R_2}{R_2 + R_4} \cdot \frac{1}{R_4}.
\]

Based on equation (5) and the above-mentioned amplifier configuration and operation process, the inductive winding coil and power amplifier can be regarded as a second-order oscillation element, and the RC network can be viewed as a first-order derivative element; thus, the electrical input dynamic model can be written as a second-order linear system.

\[
G(s) = \frac{I_d(s)}{U_i(s)} = \frac{K_0^2 (1 + T s)}{s^2 + 2\omega_n s + \omega_n^2},
\]

where \( K = \frac{R_3}{R_3 + R_3} \cdot \frac{R_2 + R_4}{R_2} \cdot \frac{1}{R_4} \) is the static coefficient conversion from the input voltage to the output current, \( T = C_c R_c \) is the corner frequency of the RC network, and \( \omega_n = 1/\sqrt{C_c L_d} \) and \( \zeta = \frac{1}{2}(R_c + R_d) \sqrt{\frac{C_c}{L_d}} \) are the natural frequency and the damping ratio of the second-order linear system describing the power amplifier and the induction coil, respectively.

As shown in figure 1, the closed magnetic circuit consists of a displacement output rod, up magnetizer, shell, down magnetizer, force output rod and GMM rod. The applied magnetic field \( H \) generated by an alternating excitation frequency \( I \) is given by

\[
H = \frac{N I}{k_i L_G},
\]

where \( N \) is the number of the excitation coil turns, \( I \) is the input current, \( k_i \) is the leakage coefficient of the magnetic flux, and \( L_G \) is the length of the drive coil for GMM rod.

Thus, the transfer function from the input voltage to the applied magnetic field can be obtained as follows

\[
G(s) = \frac{H(s)}{U(s)} = \frac{K_0^2 (1 + T s)}{s^2 + 2\omega_n s + \omega_n^2 k_i L_G}.
\]

### 3.2. Dynamic magnetization model

The Jiles–Atherton model is a physics-based ferromagnetic hysteresis model, which has been used to describe the static magnetization hysteresis of GMA. The static magnetization \( M \) can be obtained from the Jiles–Atherton model \[12, 13\].

The effective magnetic field \( H_e \) can be written as

\[
H_e = H + \alpha M,
\]

where \( \alpha \) is a mean field parameter to describe the magnetic interaction between domains.

The total magnetization \( M \) consists of the reversible magnetization \( M_r \) and irreversible magnetization \( M_i \)

\[
M = M_r + M_i.
\]

If the constant \( c \) is used to describe to the ratio of the initial magnetization to the initial anhysteretic magnetization, which ranges from 0 (completely irreversible magnetization) to 1 (completely reversible magnetization), the reversible magnetization \( M_r \) can be written as

\[
M_r = c (M_m - M_i).
\]
The anhysteretic magnetization $M_{an}$ can be obtained by the Langevin function as

$$M_{an} = M \left[ \coth \left( \frac{H_e}{a} \right) - \frac{a}{H_e} \right],$$

where $a$ is a parameter with the dimensions of the magnetic field, which characterize the shape of the anhysteretic magnetization.

Suppose the energy loss in the magnetization process is proportional to the irreversible magnetization variability; thus, an energy equation can be written as

$$d \left( -M \frac{dM}{H} dH \right) = k \left( \frac{dH}{dM} \right)^2 dH dM,$$

where $d$ takes the value $+1$ when $H$ increases and $-1$ when $H$ decreases. The parameter $k$ is the domain wall pinning constant and is used to quantify the average energy required to break the pinning site.

Equations (9)–(13) describe the magnetization hysteresis of GMA under static or quasistatic conditions, as shown in figure 4(a).

Under the dynamic applied magnetic field, by means of Maxwell equation, as shown in the figure 4(b), the induced electromotive force in the position $r$ can be written as

$$E = \frac{d(BS)}{dt} = \mu_0 \mu_G \frac{dH}{dr} r^2,$$

where $\mu_0$ is the permeability of a vacuum, and $\mu_G$ is relative permeability of the GMM rod.

The infinitesimal resistance $R$ in position $r$ can be written as

$$R = \frac{\rho_G \cdot (2\pi r)}{l_G dr},$$

where $\rho_G$ is the resistivity of the GMM rod.

The eddy current in position $r$ can be obtained as

$$I_e = \frac{E}{R} = \frac{\mu_0 \mu_G l_G r dr}{2\rho_G} \frac{dH}{dr}.$$

Accordingly, the real applied magnetic field with the eddy current effect is

$$H_e = \frac{\int_0^{R_G} \mu_0 \mu_G l_G \frac{dH}{dr} dr}{2\rho_G} = \frac{\mu_0 \mu_G R_G^3}{4\rho_G} \frac{dH}{dr},$$

where $R_G$ is the radius of the GMM rod.

The actual magnetic field $H$ yields

$$H + H_w = \frac{N_i}{k_1 l_G}.$$

Laplace transform equation (17) and substitute into equation (18) to obtain

$$H = \frac{N_i}{k_1 l_G (1 + \tau s)},$$

where $\tau$ is the time constant caused by the eddy current, $\tau = \frac{\mu_0 \mu_G R_G^3}{4k_1 l_G \rho_G}$.

To reduce the eddy current effect, the GMM rod is generally cut into many slices and bonded again, as shown in figure 4(c). In this situation, the electrical resistivity of the GMM rod $\rho_G$ can be increased. To describe this situation, a correction factor $k_1 (k_1 > 1)$ is added into the expression of the time constant $\tau$

$$\tau = \frac{\mu_0 \mu_G R_G^3}{4k_1 l_G \rho_G}.$$

3.3. Mechanical strain dynamic model

Sablik and Jiles [30] developed an expression of GMA equivalent magnetization under prestress on a GMM rod

$$H_e = H + \alpha M + H_e^t = H + \tilde{\alpha} M,$$

where $\tilde{\alpha}$ is a constant to depict the relation between the prestress and magnetic domain, $\lambda$ is a saturation magnetostrictive rate, $\sigma_0$ is the prestress on the GMM rod, and $\mu_0$ is the permeability of vacuum.

Equation (21) shows a trend that the effective magnetic field $H_e$ increases with the prestress on the rod. We presented a model to describe the relation between the magnetization and magnetostriction of GMA with the prestress effect.

Firstly, the calculation is based on the quadratic domain rotation model [23], which has been used to model the relation between the magnetization and magnetostriction of the
where \( m_G \) and \( m_d \) are the mass of the GMM rod and the displacement output rod, respectively; and \( c_G \) is the damping coefficient of the GMM rod; \( k_G \) and \( k_d \) are the stiffness of the GMM rod and the spring, respectively. \( k_G = E_G A_G / l_G \) is the stiffness of the GMM rod.

4. Model results and experimental verification

4.1. Parameter identification

In equation (8), the parameter values \( K, T, \omega_n, \zeta \) dominate the static and dynamic performance of the electrical input, which can be obtained and verified by the experimental data from the step response of the output current and the hysteresis loop under the various excited frequencies, as shown in figure 6(a). When the GMM rod is removed from the GMA, the input voltage is provided to the power amplifier, and the magnetic flux density can be measured by the pickup coil, which shows the electrical input characteristics. However, as shown in figure 6(b), if the GMM rod is placed into GMA, the magnetic flux density measured by the pickup coil will show the electrical input and magnetization properties.

As shown in figure 6(a), when a 4 V step input voltage (corresponding to a 4 A current or 50 KA m\(^{-1}\) applied magnetic field) is provided to GMA, the step response result is measured, and the transfer function can be identified. Moreover, to verify the identified transfer function, the hysteresis loop of the electrical input at various frequencies can be shown in figures 7(b)–(f)

\[
G(s) = \frac{K\omega_n^2(1 + Ts)}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{(5773.5)^2(2.7 \times 10^{-4}s + 1)}{s^2 + 2 \times 0.98 \times 5773.5s + (5773.5)^2}.
\]

The leakage coefficient of the magnetic flux \( k_l \), as shown in the equation (7), also needs be identified. As shown in figure 1, a solenoid coil is prepared from a long coil of wire wrapped in many turns. When a current passes through the coil, it creates a nearly uniform magnetic field inside, which depends upon the current and density of the turns. To identify the actual value of the magnetic flux \( k_l \), a finite element model is used, as shown in figure 8(a). Accordingly, figures 8(b)–(d) show the magnetic induction cloud picture, the magnetic induction value in the axis direction for various lengths of coil and the magnetic induction value in radial direction at various sections, respectively. Based on the simulation results from figure 8 and equation (7), \( k_l = 1.1 \).

As shown in figure 8, after the above-mentioned parameters are determined, the values of \( \lambda, M, a, c, \) and \( k \) of the Jiles–Atherton model can be identified by the experimental data of static magnetization. Then, the correction factor for the eddy current effect \( k_1 \) (\( k_1 > 1 \)) can be identified from the experimental data of the dynamic magnetization. In addition,
Figure 6. Test schematic of the magnetic field and magnetization.

Figure 7. Parameter identification of the electrical input dynamics.

Figure 8. Magnetic field simulation of GMA.
the other parameter values can be calculated directly or identified by comparison between the model results and the experimental data. All of the parameters are shown in table 1.

### 4.2. Test bench

Figure 9 shows the test bench for GMA magnetization, which consists of the signal generator, power amplifier, GMA, oscilloscope and AC fluxmeter. The signal generator provides voltage to the power amplifier, which is connected with the coil of the GMA. Then, the GMA magnetic flux density can be captured by the AC fluxmeter to calculate the magnetization of the GMA.

Figure 10 shows the test bench for GMA displacement, which consist of the signal generator, power amplifier, GMA, laser displacement sensor and force sensor. The GMA displacement can be captured by the laser displacement sensor, and the preforce can be measured and displayed in the real-time by the force sensor.

### 4.3. Prestress effect

To verify the presented magnetostrictive equation \(26\) under various prestress on the GMM rod, the experimental platform is shown in figure 10. The voltage from the signal generator is converted to current flowing into the coil by the power amplifier. The laser displacement sensor (CD5-30(A), resolution: 0.2 μm, measuring range: 1 cm, Sampling frequency: 10 kHz) can capture the displacement signal from the displacement output rod. The force sensor (output voltage: 0–5 V, measuring range: 3000 N, sensitivity: 2.0 ± 0.05 mV V\(^{-1}\)) is used to measure the preforce variation on the GMM rod in real-time.

The coil direct current is first used to generate the applied magnetic field. Then, the preforce on the GMM rod is adjusted from 0 to 1200 N, and the output displacement signal is captured by the laser displacement sensor. Figure 11 shows the variation of the output rod displacement with varying preforce, which demonstrated shows that the model equation \(26\) accurately depicts the relation between the preforce variation on the GMM rod and the output displacement variation under the input current from 3 to 5 A. The best preforce leads to the maximum output displacement in the range from 700 to 900 N. In addition, under the dynamic excitation frequency, figure 12 shows the preforce on the GMM rod variation with time at 10 Hz. The similar situation

---

**Table 1. Parameter values of GMA.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation magnetostriction (\lambda_s/\text{ppm})</td>
<td>1100</td>
<td>Mass of GMM rod (m_G/\text{kg})</td>
<td>0.12</td>
</tr>
<tr>
<td>Saturation magnetization (M_s/\text{kA m}^{-1})</td>
<td>760</td>
<td>Equivalent damp of GMM rod (c_G/\text{N s m}^{-1})</td>
<td>1280</td>
</tr>
<tr>
<td>Shape factor (a/\text{kA m}^{-1})</td>
<td>7.012</td>
<td>Relative permeability of GMM rod (\mu_G)</td>
<td>9</td>
</tr>
<tr>
<td>Domain wall interaction coefficient (\alpha)</td>
<td>–0.02</td>
<td>Resistivity of GMM rod (\rho_G/\text{Ω m})</td>
<td>(6 \times 10^{-7})</td>
</tr>
<tr>
<td>Reversibility coefficient (c)</td>
<td>0.18</td>
<td>Mass of output rod (m_e/\text{kg})</td>
<td>0.021</td>
</tr>
<tr>
<td>Pinning coefficient (k/\text{kA m}^{-1})</td>
<td>4.283</td>
<td>Resistivity of GMM rod (\rho_G/\text{Ω m})</td>
<td>(2.5 \times 10^6)</td>
</tr>
<tr>
<td>Length of GMM rod (l_G/\text{mm})</td>
<td>78</td>
<td>Stiffness of spring (k_s/\text{N m}^{-1})</td>
<td>(2.5 \times 10^6)</td>
</tr>
<tr>
<td>Length of GMM rod drive coil (L_G/\text{mm})</td>
<td>80</td>
<td>Coil turns (N)</td>
<td>(1000)</td>
</tr>
<tr>
<td>Diameter of GMM rod (d_G/\text{mm})</td>
<td>12.8</td>
<td>Permeability of vacuum (\mu_0)</td>
<td>(4\pi \times 10^{-7})</td>
</tr>
<tr>
<td>Young modulus of GMM rod (E_G/\text{GPa})</td>
<td>13</td>
<td>Magnetic leakage factor (k_l)</td>
<td>1.1</td>
</tr>
<tr>
<td>Eddy correction factor (k_L)</td>
<td>1.12</td>
<td>Voltage–current conversion coefficient (K \text{A/V})</td>
<td>1</td>
</tr>
</tbody>
</table>
to the static situation shows that the model equation (26) accurately depicts the preforce variation under the 10 Hz excitation frequency.

4.4. Magnetization

Under 20 Hz, the magnetization of GMA reflects quasistatic hysteresis. Figure 13 shows the magnetization hysteresis are excited by a large magnetic field ranging from 2 to 8 V (corresponding to 2–8 A current or 25–100 KA m$^{-1}$ applied magnetic field). The model agrees well with the experimental data.

As shown in figure 14, the presented model accurately depicts the dynamic magnetization behavior of GMA from 100 to 1000 Hz.

4.5. Displacement

Similarly, under 20 Hz, the displacement of GMA reflected the quasistatic hysteresis displacement. Figure 15 shows the displacement hysteresis excited by a large magnetic field ranging from 2 to 8 V (corresponding to 2–8 A current or 25–100 KA m$^{-1}$ applied magnetic field). The model agrees well with the experimental data.

Figure 16 shows the displacement dynamics hysteresis excited by a large frequency range from 100 to 1000 Hz. The model agrees well with the experimental data under 600 Hz. Above 600 Hz, increasing error between the model results and experimental data and declining model precision appear, which present a more complicated situation due to the varying permeability and varying Young modulus of the GMM rod.

In order to quantify the predictive precision for the present models, one can define the maximum error percentage of the magnetization and displacement for GMA as follows:

$$M_{\text{error}} = \frac{|M_m - M_{m,\text{max}}|}{M_{\text{max}} - M_{\text{min}}},$$

$$x_{\text{error}} = \frac{|x_m - x_{\text{max}}|}{x_{\text{max}} - x_{\text{min}}}.$$  

Where $M_m$, $M_e$, $M_{\text{max}}$, $M_{\text{min}}$, $x_m$, $x_e$, $x_{\text{max}}$, $x_{\text{min}}$ is the model results, the experimental value, the maximum experimental value and the minimum experimental value of the magnetization for GMA, respectively. $x_m$, $x_e$, $x_{\text{max}}$, $x_{\text{min}}$ is the model results, the experimental data, the maximum experimental value and the minimum experimental value of the displacement for GMA, respectively.

Based on the figures 13–16, equations (29), (30) and [29] in this paper, the maximum error percentage curves of the magnetization and displacement for GMA can be plotted as figure 17. It can be shown clearly in the figure 17 that the maximum error percentage of the magnetization and displacement for GMA is less than 10% under static excitation and the driving magnetic field from 0 to 100 KA m$^{-1}$ (0–8 V), unlike static excitation, which is less than 23.7% under dynamic excitation and the excitation frequency from 100 to 1000 Hz. Compared with the model predictive results from TAN [29], the maximum error percentage of the displacement for GMA is more than 40% under 300 Hz excitation frequency.

5. Discussion

For GMA, the shape of the hysteresis loop has a direct correspondence with the dynamic performance, which is governed by the electrical input, the magnetization, the eddy current and the mechanical strain. It is important to determine to what extent each dynamic process exerts influence on the output displacement dynamic behavior of GMA.

As shown in figure 18, a comprehensive comparison with the electrical input dynamics, eddy current effect and mechanical structural dynamics was performed by the displacement hysteresis loop of GMA. A ‘1’ denotes the model results including all factors, ‘2’ denotes the model results after eliminating the electrical input dynamics, ‘3’ denotes the model results after eliminating the eddy current dynamics, ‘4’
Figure 13. Quasistatic characteristics of GMA magnetization.

Figure 14. Dynamic characteristics of GMA magnetization.
Figure 15. Quasistatic characteristics of GMA displacement.

Figure 16. Dynamic characteristics of GMA displacement.
Figure 17. The maximum error percentage of the magnetization and displacement for GMA.

Figure 18. Dynamic characteristics of GMA displacement under various situations.

Figure 19. Hysteresis loops of GMA under various frequencies.
denotes the model results after eliminating both the electrical input dynamics and the eddy current dynamics, and ‘5’ denotes the results from the experimental data.

Figure 18 shows how the electrical input dynamics, magnetization dynamics and mechanical structural dynamics influence the output displacement dynamics behavior of GMA. Under 600 Hz, the presented model accurately describes the experimental data; however, decreasing precision occurs above 600 Hz because the electrical input dynamics do not provide a fast enough response to excite the GMA.

As shown in figure 19, the hysteresis loops between voltage and current, between current and magnetization, and between magnetization and displacement of GMA under various frequencies reflect the dynamic performance of the electrical input dynamics, magnetization dynamics and mechanical structural dynamics, respectively. Across the whole dynamic process of GMA, as shown in figure 19(b), magnetization dynamics play a leading role in phase delay. In contrast, as shown in figure 19(c), the mechanical structural dynamics play a chief role in amplitude attenuation.

To investigate the prestress effect on the GMM rod, when considering the various preforce from 300 to 1150 N changing as a sine wave, figure 20 shows the displacement response of the various preforce and the constant preforce at 100, 500 and 1000 Hz. The results show the prestress variation on the GMM rod can lead to static displacement variation instead of dynamic displacement variation.

In the magnetization process of GMA, the eddy current effect is a principal factor slowing the magnetization response speed, which is dominated by the radius $R_G$ and the resistivity $\rho_G$ (value shown in table 1) of the GMM rod based on equation (15). Figure 21 shows the hysteresis loop shape under various resistivities and radii of GMM rods; however, the resistivity of the GMM rod can be reduced by lamination.

6. Conclusions

To analyze the static and dynamic characteristics of GMA generated by an applied magnetic field with high frequency and high amplitude, a model including electrical input dynamics, magnetization dynamics with the eddy current effect and mechanical structural dynamics of GMA was built. Based on this model and the experimental data, a
methodology using the hysteresis loop as a tool was developed to study the static and dynamic characteristics of GMA.

In the three dynamic process of GMA, many unknown parameters, for example, the natural frequency and the damping ratio in the electrical input dynamics, five model parameters from the Jiles–Atherton model and the eddy current time constant, play an important role in accurately modeling the static and dynamic characteristics of GMA. To obtain accurate values of these unknown parameters, one test method and test bench for the experimental data of the electrical input dynamic and another for the experimental data of the magnetization dynamic were developed. Then, the parameters from the electrical input dynamics and the magnetization dynamics models were identified and verified.

The prestress on the GMM rod has a significant impact on the output static displacement of GMA, in contrast to the existing models. In this study, a hyperbolic tangent function is added to the quadratic domain rotation model to depict the actual strain with the prestress effect. The experimental data agree well the model. In addition, the optimal preforce leading to the maximum output displacement is approximately 800 N (GMM rod diameter 12.7 mm), which has been verified by the experimental data and the model results.

The electrical input dynamics perform a voltage to current conversion and energize the inductance coil to generate an applied magnetic field, which has received minimal attention and has been generally neglected in the existing studies. In this paper, a model was built to simulate the relation between the dynamic magnetization, the dynamic displacement of GMA and the electrical input dynamics. The results show the electrical input dynamics have a distinct influence on the dynamic behavior of GMA above a 600 Hz excitation frequency.

The hysteresis loop shape for a GMA system can be used as a tool to study the dynamic characteristics of the GMA, including the electrical input hysteresis loop, the static hysteresis loop, the dynamic (eddy current) hysteresis loop and the mechanical structural hysteresis loop. In this paper, under 100 Hz, the hysteresis loop shape of GMA is dominated by static hysteresis behavior. Above 200 Hz, the eddy current effect plays a stronger role. Above 600 Hz, the electrical input dynamics have a significant influence on the hysteresis loop shape. Above 800 Hz, the mechanical structural dynamics are the major factor for the dynamic performance of GMA.

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References

[28] Tan X B 2002 Control of smart actuators PhD Dissertation University of Maryland available as ISR Technical report PhD
[31] Faidley L E et al 1998 Terfenol-D elasto-magnetic properties under varied operating conditions using hysteresis loop analysis SPIE Symp. on Smart Structures vol 3329
[33] Zhu Y C and Li Y S 2014 Development of a deflector-jet electrohydraulic servovalve using a giant magnetostrictive material Smart Mater. Struct. 23 115001