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# Characteristics Analysis of Giant Magnetostrictive Actuator Applied in Jet-pipe Servovalve

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**Abstract.** In order to improve the performance of jet-pipe servovalve, a novel pilot stage for jet-pipe servovalve driven by giant magnetostrictive actuator is presented, and its working principle is given. On the basis of Jiles-Atherton's theory of magnetism, the dynamic nonlinear model of giant magnetostrictive actuator is deduced to analyze the characteristics. The simulation results shows the peak time of GMA is less than 0.5ms at the driving current of 1.5A, and the bandwidth can be reached up to 900Hz, but the static performance is worse than the torque motor applied in conventional jet-pipe servovalve.

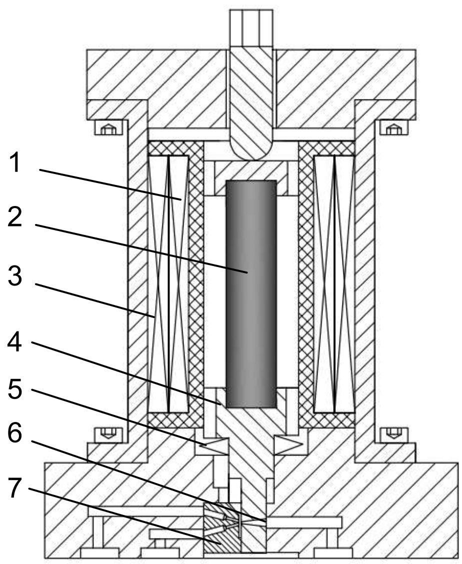
## Introduction

Hydraulic control systems are used in aerospace, ship control, industrial machinery and numerous other applications where high power, high dynamic performance, precision motion control and overload capability are desired, but space and weight are limited[1]. As the most important element in a hydraulic control system, the servovalve is both an electro-hydraulic converter and power amplification, and it's the characteristics and reliability determine the performance of hydraulic control system [2]. So, to improve the performance of hydraulic control systems, it is essential to develop new types of servovalves based on new technology and new materials.

Giant magnetostrictive actuator (GMA) based on giant magnetostrictive materials (GMM) has large blocked force, high energy density, and large bandwidth capabilities. In addition, GMA has no moving parts and are therefore, mechanically less complex than conventional torque motor applied in servovalve [3,4]. Hence the reliability of jet-pipe servovalve driven by GMA is higher than conventional servovalve. So, the research on the characteristics of GMA is important to develop a higher performance servovalve.

## Jet-pipe Servovalve by GMA

As shown in Fig.1, the pilot stage of jet-pipe servovalve consists mainly of GMA and jet-pipe hydraulic amplifier. GMA includes a bias solenoid coil used for providing a bias magnetic field, a driving solenoid coil generating a control magnetic field, a GMM rod, an output rod and a spring using for applying a pre-stress on GMM rod to obtain a larger magnetostrictive strain with same magnetic field. When the sign of magnetic field produced by the driving solenoid coil is the same as the sign of the bias magnetic field, the length of GMM rod elongates. If the sign of magnetic field produced by the driving solenoid coil is opposite to the sign of bias magnetic field, the length of GMM rod is shorter than it in initial condition that the total magnetic field equals to the bias magnetic field. In a jet-pipe hydraulic amplifier, the pressure energy of the fluid is converted into kinetic energy at the nozzle exit and is then reconverted as pressure energy in receiver holes. When the nozzle is centered between the two receiver holes in the receiver, the pressure difference between the two receiver holes is zero. However, when the nozzle is moved toward one of the receiver holes by the GMA, the pressure at this receiver hole is greater than the other receiver hole, thus displacing the spool position.




1. Driving solenoid coil, 2. GMM rod, 3. Bias solenoid coil, 4. Output rod, 5. Spring, 6. Nozzle, 7. Receiver

Fig. 1. Configuration of the pilot stage for jet-pipe servovalve driven by GMA

**The model of Giant magnetostrictive actuator**

In order to improve the usage of magnetic energy, the magnetic circuit is closed, and the magnetic reluctance of magnetic circuit is approximately equal to the magnetic reluctance of giant magnetostrictive rod, so the total magnetic field $H$ is given by

$$H = \frac{NI}{k_{\mathrm{f}} L} + H_{\mathrm{b}} \tag{1}$$

where $N$ is the number of the coil turns, $k_{\mathrm{f}}$ is the leakage coefficient, $L$ is the length of GMM rod. $H_{\mathrm{b}}$ is the bias magnetic field.

Beside the magnetic field calculating from Eq. (1) and Eq. (3), the effective field applied on giant magnetostrictive rod should include the magnetic field arising from magnetic interaction between domains and magnetic field arising from magnetic interaction between domains.

$$H_e = H + \alpha M + \frac{9\lambda_S \sigma}{2\mu_0 M_s^2} M = H + \gamma M \tag{2}$$

where $\alpha$ is a dimensionless term representing the strength of the coupling of magnetic moments to the magnetization, $\sigma$ is the prestress applied on giant magnetostrictive rod, $\mu_0$ is the permeability of free space, $\lambda_{\mathrm{S}}$ is the saturation magnetostrictive, $M_{\mathrm{S}}$ is the saturation magnetization.

The anhysteretic magnetization $M_{\mathrm{a}}$ can be obtained from the Langevin function

$$M_{\mathrm{a}} = M_S \left[ \coth\left(\frac{H_{\mathrm{e}}}{a}\right) - \frac{a}{H_{\mathrm{e}}} \right] \tag{3}$$

where $a$ is the constant of the material dependent in part on microstructure.

Due to the hysteresis effect, the conversion process from the magnetic field to magnetization is complicated and nonlinear, but the relationship between the magnetic field $H$ and the magnetization $M$ can be described by Jiles-Atherton's theory of magnetism [4, 5].

$$\begin{cases} M_{\mathrm{i}} = M_{\mathrm{a}} - \delta k \dfrac{\mathrm{d}M_{\mathrm{i}}}{\mathrm{d}H_{\mathrm{e}}} = M - M_{\mathrm{r}} \\ M_{\mathrm{r}} = c\left(M_{\mathrm{a}} - M_{\mathrm{i}}\right) \end{cases} \tag{4}$$

where $M_{\mathrm{i}}$ is the irreversible magnetization, $M_{\mathrm{r}}$ is the reversible magnetization, $\delta$= +1 when $H$ is increasing and $\delta$ = -1 when $H$ is decreasing, $c$ is the reversibility coefficient, $k$ is the pinning parameter.

As the discussion in Ref. [5], the magnetostrictive $\lambda$ is given by

$$\lambda = \frac{3}{2}\frac{\lambda_S}{M_S^2}M^2 \quad (5)$$

So, the magnetostrictive force can be obtained from Hooke's law,

$$F = E^{\mathrm{H}} A_{\mathrm{r}} \lambda \quad (6)$$

where $E^{\mathrm{H}}$ is the elastic modulus, $A_{\mathrm{r}}$ is the cross-sectional area of GMM rod.

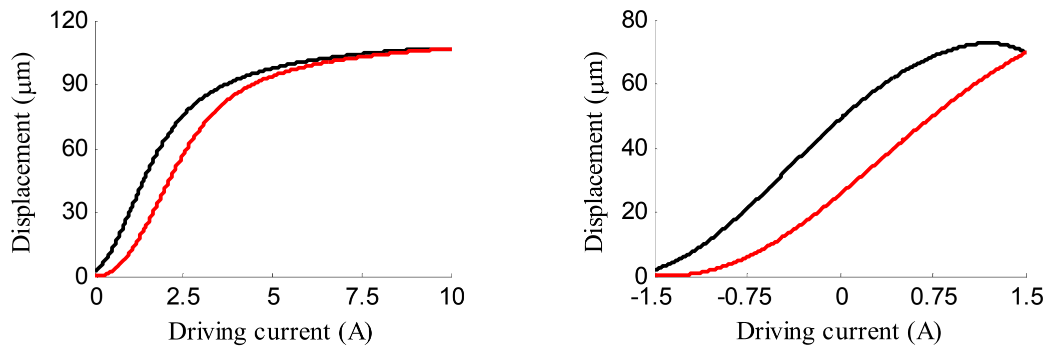
The Lumped parameter model of giant magnetostrictive transducer is a mass-spring-damping system[3]. Therefore, the model of giant magnetostrictive transducer can be described as

$$F = m\frac{\mathrm{d}^2 y}{\mathrm{d}t^2} + C\frac{\mathrm{d}y}{\mathrm{d}t} + Ky \quad (7)$$

where $y$ is the output displacement of GMA, $m$, $C$ and $K$ are the equivalent mass, equivalent damping and equivalent stiffness of GMA, respectively.

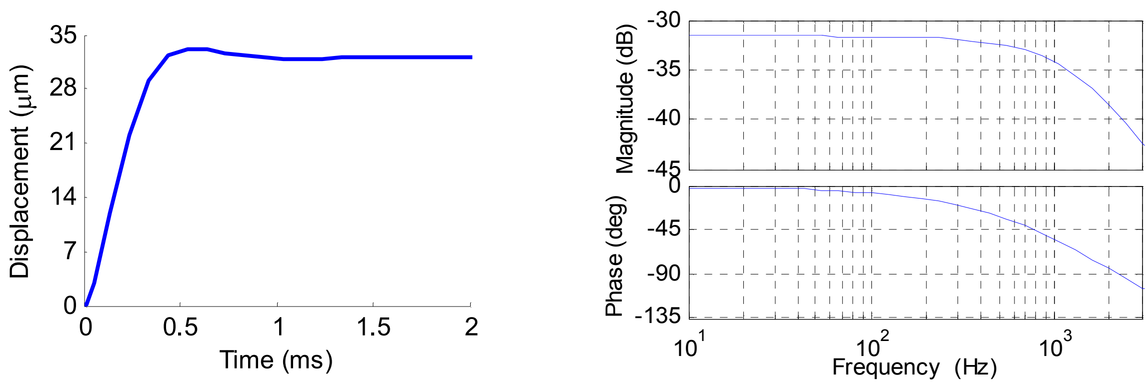
## Simulation and Analysis

The simulation parameters for GMA are shown in Table1, and the results are shown in fig.2 and fig.3.




(a) Bias current at 0 (b) Bias current at 2A

Fig. 2. The displacement of GMA versus the driving current




(a) Step response (b) Frequency response

Fig. 3. The dynamic characteristic curves of GMA

Fig.2 (a) shows that the shipment between the displacement and the driving current has a better linearity at the driving current of 0.5-3.5A. So, the bias current is set to equal to 2A when the bias driving solenoid coils has the same turns as the driving solenoid coils, and the range of driving current becomes -1.5A to 1.5A, as shown in fig.2(b). Fig.3 shows that the peak time of GMA is less than 0.5ms at the driving current of 1.5A, and the bandwidth can be approached to 900Hz.

The comparison of static performance between GMA and torque motor applied in conventional jet-pipe servovalve is shown as Table 2. It shows that linearity, hysteresis and symmetry of GMA are worse than the latter.

Table 1 The values of simulation parameters for GMA

| | | | | | |
|---|---|---|---|---|---|
| $L$ | Length of GMM rod (mm) | 10 | $k$ | pinning parameter (A/m) | 6000 |
| $D$ | Diameter of GMM rod (mm) | 8 | $c$ | reversibility coefficient | 0.2 |
| $N$ | Turns of driving solenoid coils | 1200 | $a$ | Shape parameter (A/m) | 5000 |
| $K_f$ | Leakage coefficient of magnetic flux | 1.1 | $E^H$ | Elastic modulus (Gpa) | 17 |
| $M_S$ | Saturation magnetization (A/m) | $7.65\times10^5$ | $m$ | Equivalent mass (kg) | 0.2 |
| $\lambda_S$ | Saturation magnetostrictive | $1000\times10^{-6}$ | $C$ | Equivalent damping (Ns/m) | 2954 |
| $\gamma$ | Mean field corrected for stress | -0.02 | $K$ | Equivalent stiffness (N/m$^2$) | $1.67\times10^7$ |

Table 2 The comparison of static performance between GMA and conventional torque motor

| category | Linearity | Symmetry | Hysteresis | Threshold |
|---|---|---|---|---|
| conventional torque motor | ＜7.5% | ＜10% | ＜5% | ＜1% |
| GMA | 53% | 20% | 48% | 0.1% |

## Conclusions

GMA has a better dynamic performance than conventional torque motor applied in servovalve, but its linearity, hysteresis and symmetry are larger than the torque motor, so when GMA is applied in servovalve, it is necessary to improving the static performance by closed-loop control.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## References


[1] S Karunanidhi, M Singaperumal. *Design, analysis and simulation of magnetostrictive actuator and its application to high dynamic servovalve* [J]. Sensors and Actuators A, 157(2010), p185.

[2] Yuesong Li, Yuchuan Zhu, Hongtao Wu, etc. *Parameter Optimization of Jet-pipe Servovalve Driven by Giant Magnetostrictive Actuator* [J].Acta Aeronautica et Astronautica Sinica, 32(2011), p1336.(in Chinese)

[3] Yuesong Li, Yuchuan Zhu, Hongtao Wu, etc. *Research on Displacement-sensing model and hysteresis loop of gaint magnetostrictive actuator* [J].Journal of Mechanical Engineering, 48(2012), p169. (in Chinese)

[4] D C Jiles. *Modeling the effects of eddy current losses on frequency dependent hysteresis in electrically conducting media*[J]. *IEEE Transactions on magnetic*s.30(1994), p4326.

[5] F T Calkins, R C Smith, A B Flatau. Energy-based hysteresis model for magnetostrictive transducers[J]. *IEEE Transactions on magnetic*s.36(2000), p429.