Journal of Physics: Conference Series

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Institute of Physics Publishing Journal of Physics: Conference Series **13** (2005) 446–449
doi:10.1088/1742-6596/13/1/103 7th International Symposium on Measurement Technology and Intelligent Instruments

Research on Giant Magnetostrictive Micro-displacement actuator with self-adaptive control Algorithm

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Abstract. Giant magnetostrictive micro-displacement actuator has some unique characteristics, such as big output torque and high precision localization which can be in the nanometer scale. Because the relation between input magnetic field and output strain of giant magnetostrictive micro-displacement actuator exhibits hysteresis and eddy flow, the actuator has to be controlled and used in low input frequency mode or in static mode. When the actuator is controlled with a high input frequency (above 100Hz), the output strain will exhibit strong nonlinearity. This paper found hysteresis and nonlinearity dynamic transfer function of the actuator based on Jiles-Atherton hysteresis model. The output strain of Jiles-Atherton hystersis model can reflect real output of actuator corresponding to the real input magnetic field, and this has been verified by experiment. Against the nonlinearity generated by hysteresis and eddy flow in this paper, the output strain of actuator is used for feedback to control system, and the control system adopted self-adaptive control algorithm, the ideal input and output model of actuator is used for a reference model and a hysteresis transfer function for the actuator real model. Through experiment, it has been verified that this algorithm can improve the dynamic frequency of the giant magnetostrictive micro-displacement actuator and guarantee high precision localization and linearity between the input magnetic field and output strain of the actuator at the same time.

1. Introduction

Giant magnetostrictive material （$Tb_{0.23}Dy_{0.75}Fe_{1.95}$） is a kind of rare earth compound, and has strong magnetostriction effect. It has some unique features, such as large strain（λ=1000-1500ppm）, high magnetic-mechanical coupling coefficient（≈0.73）,high frequency response and large output torque. A giant magnetostrictive micro-displacement actuator which is developed with giant magnetostrictive material and giant magnetostriction effect changes electromagnetic energy into mechanical energy and has large output torque, high resolution of displacement and frequency response, can be universal, used in micro-processing, ultra-precise micro-dive and focus control etc.

The magnetic field of the giant magnetostrictive micro-displacement actuator is composed of a magnetic field produced by an electric solenoid and magnetization of the giant magnetostrictive material. If the actuator works in static or low frequency alternating magnetic field, hysteresis and eddy flow of the actuator may be ignored, and the output displacement and input current of the actuator can present linearity. But if the actuator is applied in focus control which needs high frequency response, the hysteresis and eddy flow may induce the output and input of the actuator appear non-linear. So the non-linearity model of the actuator is important for improving the actuator application. Calkins[2] created a strain and quadratic hysteresis model of magnetization intensity based on the

Jiles—Atherton[2] ferromagnetic hysteresis model and magnetic domain magnetization model, and this model is a low order differential equation. This model only needs six physical parameters, so parameters can be determined. But this model doesn't involve dynamic performance of the system and can't inverse the working state of the actuator in high frequency response. In this paper, the non-linearity dynamic equation of the actuator has been presented, and this equation is composed of the Jiles—Atherton model and the dynamic equation of the actuator. Moreover, the closed loop system of the actuator adopts a self-adaptive control Algorithm to improve output accuracy and dynamic performance.

2. Principle and control model of giant magnetostrictive micro-displacement actuator

2.1. Principle of actuator

The Structure of the giant magnetostrictive micro-displacement actuator shown as figure 1, an electric solenoid produces magnetic field which can drive the giant magnetostrictive rod. A bolt supplies a pre-load for the system, while a permanent magnet supplies bias magnetic field. A flexible hinge changes the strain of giant magnetostrictive into output displacement.

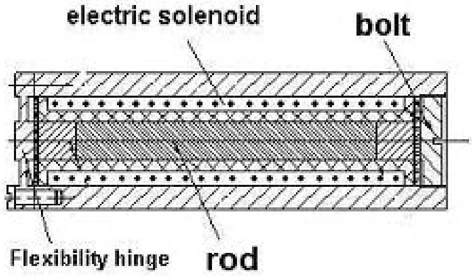

Figure 1. Structure of giant magnetostrictive micro-displacement actuator

2.2. Control model

According to the Jiles—Atherton hysteresis model for a ferromagnetic material, Calkins created hysteresis model of giant magnetostrictive material. This model describes a hysteresis non-linearity relation of the input current and output magnetization. And the model is shown as follow:

$$H(t) = nI(t) \tag{1-a}$$

$$H_{eff}(t) = H(t) + \alpha M(t) + H_{\sigma}(t) \tag{1-b}$$

$$M_{an}(t) = M_s[\coth(\frac{H_{eff}(t)}{a}) - (\frac{a}{H_{eff}(t)})] \tag{1-c}$$

$$\frac{dM_{irr}}{dt}(t) = n\frac{dI}{dt} \cdot \frac{M_{an}(t) - M_{irr}(t)}{k\delta - \bar{\alpha}[M_{an}(t) - M_{irr}(t)]\frac{dM_{irr}}{dM}} \tag{1-d}$$

$$M_{rev}(t) = c[M_{an}(t) - M_{irr}(t)] \tag{1-e}$$

$$\lambda = \frac{3\lambda_s}{2M_s^2}M^2 \tag{1-f}$$

Where H is magnetic field produced by electric solenoid, H_{eff} is effective magnetic field determined by inner magnetic moment of bar , anhysteresis magnetizatioan intensity M_{an} and irreversible magnetization intensity M_{irr} , H_{σ} produced by pre-load; M_s is saturation magnetization intensity($\approx 7.9 \times 10^5 A/m$); $\bar{\alpha} \equiv \alpha + (9/2)(\lambda_s \sigma / \mu_0 M_s^2)$; c is reversible coefficient, obtained by experiment data with least square, λ_s is saturation magnetostriction coefficient($\approx 995 \times 10^{-6}$).For some actuator, when α 、 a 、 k 、 c 、 M_s and λ_s are all confirmed, relation between input current and output of displacement can be determined.

3. Control system of actuator

3.1. Dynamic model of actuator

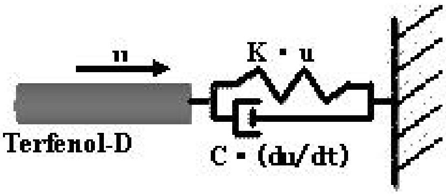

Figure 2. Dynamic model

In the Dynamic model of the actuator shown as figure2, the load is mass-spring-damping load. One end of bar fixed x=0, is applied to pre-load σ_0, and the other end drives load. Function of dynamic model as follow:

$$F = \sigma A_r = -(M\ddot{u} + C\dot{u} + Ku + \sigma_0 A_r) \tag{2}$$

Where M is mass of system, C is damping coefficient of system, K is rigidity coefficient of system; F 、 u 、 σ_0 、 A_r are separately output torque, displacement, pre-load, cross-sectional area of bar. Integrating formula (1) and formula (2), using Laplace transform and neglecting irreversible magnetization intensity M_{irr}, the ideal dynamic transfer function of system is obtained:

$$G_m = \frac{3\lambda_s H_0}{(MS^2 + CS + K)(3a - M_s\overline{\alpha})^2} \tag{3}$$

3.2. Self-adaptive control Algorithm

Because of the effect of hysteresis and eddy flow, the magnetic field of the actuator will alter non-linearly as the frequency of input current changes. Integrating the Jiles—Atherton hystersis model and corresponding control method is an ideal method for solving the non-linearity of the giant magnetostrictive micro-displacement actuator.

As shown in figure 3, the self-adaptive control method is adopted in the actuator system. The dynamic non-linearity model of the actuator is taken as an ideal reference model. In formula 3, $X_m(s)$ is the ideal distance output without hysteresis and eddy flow disturbance. $X_o(s)$ is the bar's actual output. The error e(s) and de(s)/dt are inputs of fussy arithmetic. The experiment uses some proper fussy control regulation and fussy illation to regulate parameters K_i , K_p and K_d of PID controller on line, and then alter the bar's output to get the ideal static value of distance change.

4. Experiment and simulation

M_t is the weight of bar, E^H, A_t , C_t ,L_t, ρ and N indicate Yong's modulus, damping coefficient, cross-sectional area, length, density, and winding circles, letting M_t=0.058Kg, E^H=3.5×10^{10}N/m^2, C_t =2.95×10^3Ns/m, A_t=78.54mm^2,L_t=10mm,ρ=9.25g/cm^3, N=1000.

The Dynamic system of the actuator is shown as figure 2. It is composed of a bar and a load, so its model parameters are made up of these two parts. M=M_t+M_f=1.058Kg, where M_f is load weight; K=6.256×10^7N/m rigidity coefficient; C=10×10^3Ns/m damping coefficient; λ_s=1300×10^{-6} saturation magnetostriction coefficient; M_s=7.7×10^5A/m magnetization intensity.

Basing on parameters listed above, experiment and simulation are done as follows.

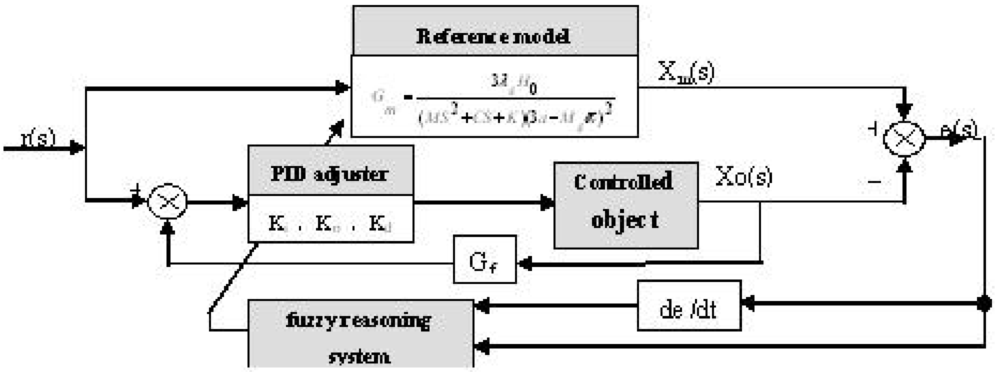

Figure 3. Control system diagram of actuator

As shown in figure 4, when the input current of the actuator is given a unit phase step, the output of the actuator has some different results. When it is not self-adaptive, and the cure is actual line'-' in figure 4, for the output to be steady state needs a long time .When adopting self-adaptive, and the curves are dotted line '--'and'-*' in figure 4, the system needs 60us to reach steady state and system won't oscillate.

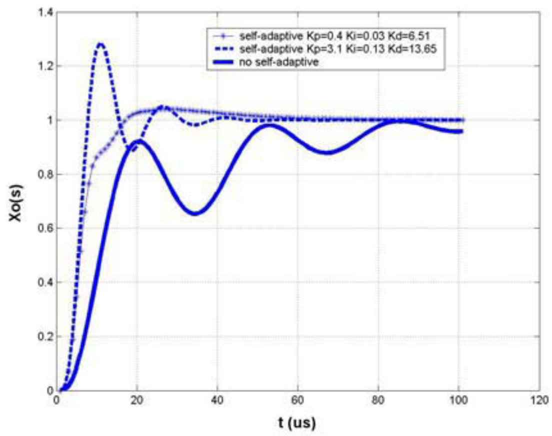

Figure 4. Self-adaptive and no self-adaptive data curve

5. Conclusion

The giant magnetostrictive material （$Tb_{0.27}Dy_{0.73}Fe_2$） is a sort of novel ferro-magnetic material, and the giant magnetostrictive micro-displacement actuator is developed with ferro-magnetic performance and magnetostrictive theory. It has a big output torque, high frequency response, and no creep deformation. In this paper, the Jiles—Atherton hysteresis model and dynamic model of the actuator have been integrated, and adopted a self-adaptive control Algorithm in the closed loop of the system. From the Experiment and simulation, the method has been verified to solve the non-linearity phenomenon of the giant magnetostrictive micro-displacement actuator, when the actuator has high input frequency.

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