Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Theory and experiment of observer based magnetostrictive self-sensing actuator*

Zhi-feng TANG†, Fu-zai LV†‡, Zhan-qin XIANG
(*Modern Manufacture Engineering Institute, Zhejiang University, Hangzhou 310027, China*)
†E-mail: tangzf2001@yahoo.com; lufuzai@yahoo.com

Received June 10, 2007; revision accepted Sept. 5, 2007; published online Nov. 10, 2007

Abstract: Giant magnetostrictive actuators (GMAs) often work in a close-loop feedback system. This system needs independent sensors which may be difficult to be fixed, besides, excessive sensors may cause more unpredicted problems in a large system. This paper aims to develop a self-sensing GMA. An observer based on piezomagnetic equations is constructed to estimate the stress and strain of the magnetostrictive material. The observer based self-sensing approach depends on the facts that the magnetic field is controllable and that the magnetic induction is measurable. Aiming at the nonlinear hysteresis in magnetization, a hysteresis compensation observer based on Preisach model is developed. Experiment verified the availability of the observer approach, and the hysteresis compensation observer has higher tracking precision than linear observer for dynamic force sensing.

Key words: Magnetostrictive, Self-sensing actuator, Hysteresis, Giant magnetostrictive actuators (GMAs)
doi:10.1631/jzus.A071402 **Document code:** A **CLC number:** TH113; TH161

INTRODUCTION

Giant magnetostrictive actuators (GMAs) exhibit well-known advantages such as large forces and rapid response but on the other hand the disadvantages of non-linear behavior when driven in the large signal range (Clephas and Janocha, 1998). Therefore, sensors are often needed to make up a close-loop system. However, redundant system elements bring great difficulties in structural control for large space structures. If a single magnetostrictive transducer can be used to play the role of both sensor and actuator, it will reduce the number of system elements and realize truly collocated control. Bridge circuit coupled with a linear model is an original approach for magnetostrictive and piezoelectric self-sensing actuator, but it could not sense DC signals and is hardly to solve the problems of impedance mismatching, drift and instability (Pratt and Flatau, 1993). Kuhnen *et al.*(2007) described an integral feedback controlled self-sensing magnetostrictive actuator by sensing the variation of the magnetic flux in the material. Jones and Garcia (1997) described an approach of OBSS (Observer Based Self-sensing) to a piezoelectric actuator. This paper discusses the possibility of applying OBSS to magnetostrictive actuator, which uses magnetic field and magnetic induction information coupled with the linear piezomagnetic constitutive relations to estimate the stress and strain states. Aiming at the significant hysteresis in GMA, a real time numerical compensation algorithm based on Preisach model is adopted in the nonlinear observer.

LINEAR OBSERVER

Similar to OBSS for piezoelectric material that uses the third kind of piezoelectric constitutive equations (Jones and Garcia, 1997), linear piezomagnetic constitutive equations under the third kind of boundary condition for magnetostrictive materials are:

‡ Corresponding author
* Project supported by the National Natural Science Foundation of China (No. 50105019) and the China Postdoctoral Science Foundation (No. 20060390337)

$$\varepsilon=\sigma/E_y^B+g_{33}B, \quad (1)$$
$$H=-g_{33}\sigma+v^\sigma B, \quad (2)$$

where ε is the strain, σ is the stress, E_y^B is Youngs Modulus, g_{33} is piezomagnetic strain coefficient and v^σ is magnetic reluctivity. If magnetic field strength H can be controlled and magnetic induction B can be measured (or vice versa), it is possible to calculate the stress σ and strain ε explicitly. Substituting $\varepsilon=x/l$ and $\sigma=F/A$ into Eqs.(1) and (2), the output displacement x and force F of giant magnetostrictive material (GMM) rod become

$$x=lF/(AE_y^B)+g_{33}lB, \quad (3)$$
$$F=A(H-v^\sigma B)/g_{33}. \quad (4)$$

For a straight moving type of GMA, its output displacement equals the displacement of GMM rod, and its output force equals the force of GMM rod subtracting the pre-stress against the rod. Eqs.(3) and (4) can be depicted clearly in Fig.1, which is the schematics of linear observer based self-sensing for a GMA. It has been deduced that the magnetic field strength in GMA is $H\approx0.897$ ni when the coil power losses are considered (Engdahl, 2000). Therefore, $G_1=0.897n$, where n is the turns per unit length of the coil. In Fig.1, i is driven current to the GMA, and G_2 are the methods to obtain magnetic induction B. For example, placing an inner sensing coil is a choice to measure B, but it is used only for dynamic application and mutual induction is also plagued. So we use a lamellate hall sensor fixed on the surface of the GMM rod to measure the magnetic induction in the GMA (Fig.4). Parameters of E_y^B, g_{33} and v^σ should be calibrated by independent sensors before testing.

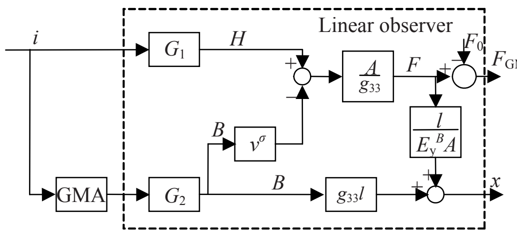

Fig.1 Schematics of linear observer

HYSTERESIS COMPENSATION OBSERVER

Linear observer becomes inaccurate as driven in large signals due to the hysteresis. The most serious nonlinear hysteresis occurs in the magnetization between H and B. Many research papers show that the strain of GMM has nearly linear relationship with magnetic induction B (Restorff *et al*., 1990; Kuhnen *et al*., 2004; Jia *et al*., 2002). If we can replace the linear block v^σ in Fig.1 with a nonlinear model which describes the hysteresis relationship between B and H, the observing result may be more accurate. The classical Preisach model is universally known for its satisfaction and acceptable computational cost to describe rate-independent memory phenomena (hysteresis) (Davino *et al*., 2005). Therefore, this paper aims at building a hysteresis compensation observer based on classical Preisach model.

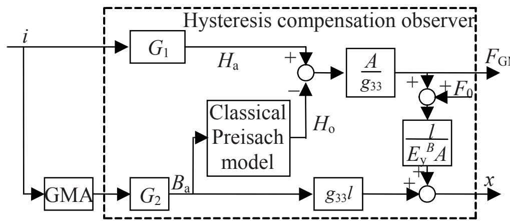

Fig.2 Schematics of hysteresis compensation observer

In Fig.2, H_a is the magnetic field strength in the center axial line of a GMM rod, and H_o is the magnetic field strength compensation value through the classical Preisach model. If the external load is zero, $H_o=H_a$ since the work condition is mechanically free while building the Preisach model of GMA. This assures that the force sensing signal of the observer F_{GMA} is zero.

Compare the hysteresis compensation observer with the linear observer, we can get the following results theoretically: (1) The force signal of a hysteresis compensation observer is the actual output force of the GMA, while the force signal of a linear observer is the output force of the GMM rod. (2) The displacement signal of a hysteresis compensation observer nearly equals that of a linear observer, because in the hysteresis compensation observer the displacement value generated at the magnetic induction branch is much more than that generated at the force branch. (3) If the GMA is in the condition of mechanically free, use of the linear observer is more practical since the external load is zero. If the output force of GMA is time varying, use of the hysteresis compensation observer could get more accurate sensing force value.

HYSTERESIS COMPENSATION ALGORITHM

The discretization of Preisach plane and measuring a series of the first order hysteresis reversals curves is a most common method to build the Preisach model (Davino *et al.*, 2005). To control a magnetic field strength H is much easier than to control a magnetic induction B in practical application of GMA. So, in general, H is selected as the input of Preisach model while B is the hysteresis output, which is called Preisach positive model or prediction issue. In Fig.2, we need to know H_o after measuring B_a, which is called Preisach inverse issue or hysteresis compensation. We have presented a numerical realization of classical Preisach model and verified its effectiveness for GMA (Tang *et al.*, 2007). The positive issue will not be presented again in the paper. The inverse issue of the Preisach model is always a difficult one. In this paper we use a real time numerical algorithm for hysteresis compensation.

A least squares method is used to the linear fit of the magnetic hysteresis loop which is shown in Fig.3. The linear relationship of B and H is $B=6.36\times10^{-6}H+0.013$. As shown in Fig.4, the measured series of magnetic induction $\{B_c(k), k=1,\dots,N\}$ are known, and the theoretical series of magnetic field strength $\{H_t(k), k=1,\dots,N\}$ can be obtained by linear fitting of magnetic hysteresis loop. The detailed explanation of the hysteresis compensation algorithm is presented as follows.

Given that the measured series of magnetic induction $\{B_c(k), k=1,\dots,N\}$ and hysteresis compensation series $\{H_r(k-1)\}$, it needs to know the kth hysteresis compensation value $H_r(k)$.

First, the kth theoretical value of magnetic field strength $H_t(k)$ can be solved by linear fitting model. Then $H_t(k)$ and the known $\{H_r(k-1)\}$ construct a new sequence which can be input to the Preisach positive model. The predicted magnetic induction $B_p(k)$ can be obtained. If the predicted value $B_p(k)$ is greater than the measured value $B_c(k)$ and exceeds the control error e, then $H_m=H_t(k)-\Delta H$, where ΔH is the controlled interval of magnetic strength H. Otherwise, $H_m=H_t(k)+\Delta H$, where H_m and $\{H_r(k)\}$ construct a new sequence and are input to the Preisach positive model again. Iterate above procedure until the difference between the predicted value $B_p(k)$ and the measured value $B_c(k)$ is less than the control error e.

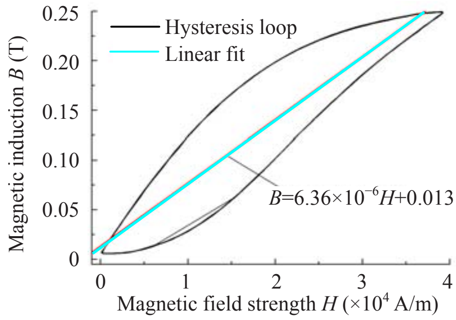

Fig.3 Hysteresis loop and linear fit

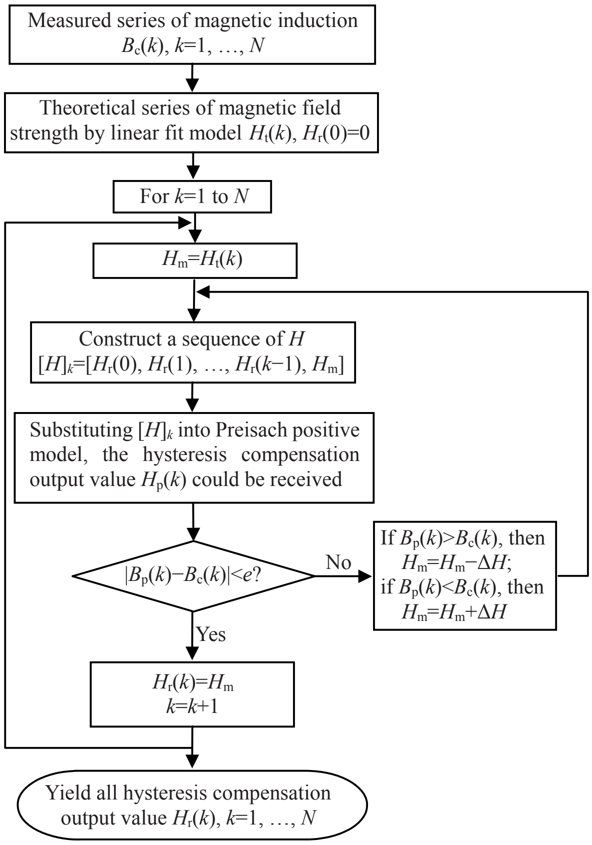

Fig.4 Algorithm flow of hysteresis compensation

$B_c(k)$: the kth measured B; $B_p(k)$: the kth predicted B; $H_t(k)$: the kth theoretical value of H by linear fitting model; $H_r(k)$: the kth H after theoretical compensation; H_m: intermediate variable; e: control error

EXPERIMENTAL VERIFICATION

An experimental test system depicted in Fig.5 is set up to validate the observer based magnetostrictive self-sensing actuator. A force sensor is fixed in the GMA between the preloaded washer springs and the upper bracket to measure the output force of the

GMM rod. A LVDT sensor is used to measure the displacement of the GMA. The two sensors are independently incorporated for purposes of comparison and parameters calibration in the observer. A hall sensor is integrated in the GMA. All signals are sent to the data acquisition device (PXI6071E), which is installed in the NI frame (PXI1031). The observer is programmed in the LabVIEW environment. The linear power amplifier is LVC5050 made by AETechron. The function generator is AFG310 made by Tektronix, which can generate arbitrary waveform.

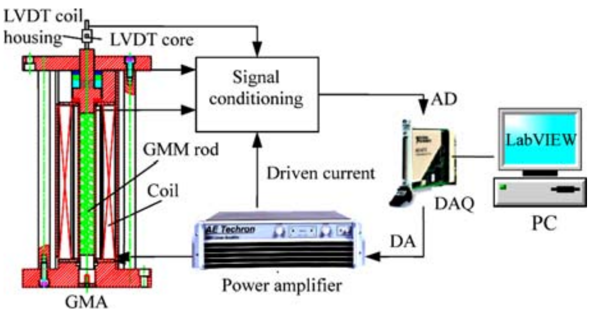

Fig.5 Schematic drawing of the experimental system

Since it is not convenient to measure the force and displacement simultaneously, two comparatively easy experiments below are tested to verify the linear observer and the hysteresis compensation observer. Experiment 1 is used to verify the availability of linear observer while the GMA is freely movable as Fig.5. Experiment 2 is used to verify the availability of sensing variable force while the GMA is blocked as Fig.6.

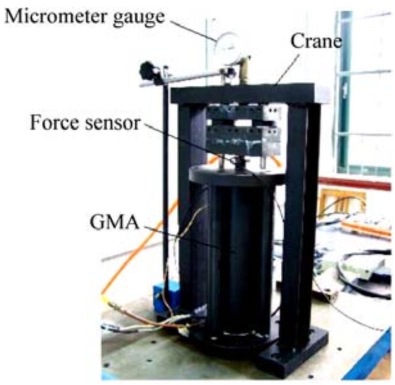

Fig.6 A blocked GMA for dynamic force sensing test

Experiment 1 GMA is free to move axially (Fig.5), and external load is zero. The pre-stress is 0.5 MPa. A linear observer is used to sense the static displacement and the force of the GMM rod.

Firstly, ten cycles of 1 Hz triangle current waveform are input to the GMA for calibration. A steepest descent optimum algorithm is carried out to search the best fit for the data, which yields $\nu^{\sigma}=1.61\times10^{5}$ A^2/N, $g_{33}=1.75\times10^{-3}$ A·m/N and $E_y^B=1.5\times10^{10}$ N/m^2.

An input current sequence is constructed by seven driven current value, that is {0.5 A, 0.2 A, 0.8 A, 0.3 A, 0.5 A, 0.2 A, 0.8 A}, each of which lasts 1 s. Fig.7a is the comparison of displacement measurements using linear observer and LVDT sensor. Fig.7b is the comparison of force measurements using linear observer and force sensor.

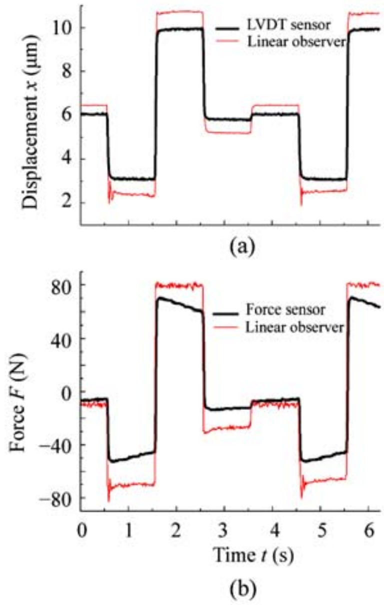

Fig.7 Comparison of (a) displacement measurements using linear observer and LVDT sensor and (b) force measurements using linear observer and force sensor

As shown in Figs.7a and 7b: (1) Linear observer can sense static displacement with a maximum error of 0.8 μm in the range of 10 μm. The error ratio is 8%. (2) Linear observer can also sense static force with a maximum error of about 30 N in the range of −50 N to 70 N. The error ratio is 25%.

The observer sensing errors include parameter calibration error, magnetic induction estimation error and nonlinear error originated by the GMM itself. Why is the force sensing error much more than the displacement sensing error? It is believed that the displacement part caused by the magnetic induction branch is larger than the part caused by the force branch. Take a look at Fig.1, the hysteresis between B

and H has much more effects on force sensing, therefore it is more important to take into account of the hysteresis for force sensing.

Experiment 2 GMA is working at a mechanical blocked status depicted in Fig.6. A micrometer gauge is used to measure the distortion of the crane to assure the blocked status of the GMA. The pre-stress of GMA is 0.5 MPa. The linear observer and hysteresis compensation observer are used to sense the output force of the GMA separately.

To test the performance of hysteresis compensation observer, a length of 4096 points and time of 4 s random waveform is edited in the signal function generator. The signal is amplified to the same waveform current signal through the linear power amplifier. Fig.8a shows the force sensing result using linear observer, which has already subtracted the pre-stress. Fig.8b shows the force sensing result using the hysteresis compensation observer.

Figs.8a and 8b show that both linear observer and hysteresis compensation observer can sense force, but obviously the hysteresis compensation observer has higher tracking precision than the linear observer for dynamic force sensing.

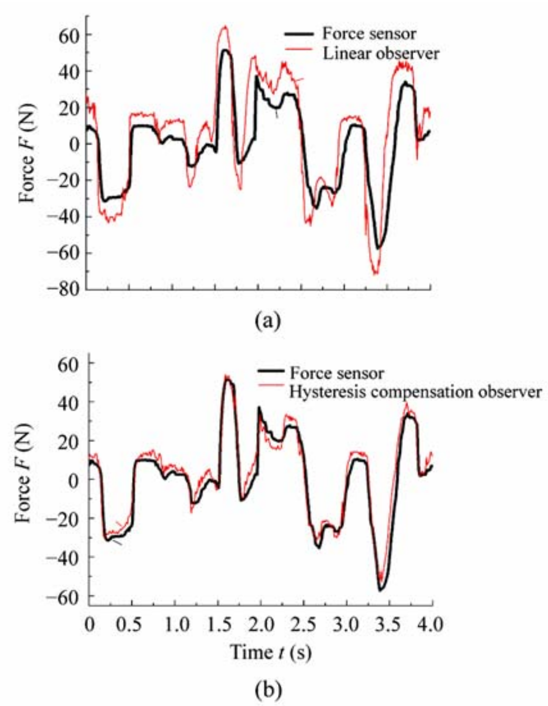

Fig.8 Self-sensing force using linear observer (a) and hysteresis compensation observer (b)

CONCLUSION

A novel approach of self-sensing magnetostrictive actuator has been presented. The approach involves by using state estimation technique to develop an observer based on piezomagnetic equations, and to realize the self-sensing of two mechanical states: displacement and force. Experiment proved the availability of linear observer. Aiming at the significant error of self-sensing force signal using linear observer, we developed a hysteresis compensation observer based on Preisach model. A real time numerical algorithm for hysteresis compensation is pointed out. Experimental result showed a good tracking performance between the self-sensing force signal and an independent force sensor signal using hysteresis compensation observer.

References

Clephas, B., Janocha, H., 1998. Simultaneous sensing and actuation of a magnetostrictive transducer. *Proceedings of SPIE*, **3329**:174-184. [doi:10.1117/12.316891]

Davino, D., Natale, C., Pirozzi, S., 2005. A fast compensation algorithm for real-time control of magnetostrictive actuators. *Journal of Magnetism and Magnetic Materials*, **290-291**:1351-1354. [doi:10.1016/j.jmmm.2004.11.435]

Engdahl, G., 2000. Handbook of Giant Magnetostrictive Materials. Academic Press, Sa Diego.

Jia, Z.Y., Yang, X., Guo, D.M., Guo, L.S., 2002. Study on control methods of microdisplacement actuator on giant magnetostrictive materials. *Chinese Journal of Scientific Instrument*, **23**(3):288-301.

Jones, L.D., Garcia, E., 1997. Novel approach to self-sensing actuation. *Proceedings of SPIE*, **3041**:305-314. [doi:10.1117/12.275655]

Kuhnen, K., Janocha, H., Schommer, M., 2004. Exploitation of Inherent Sensoreffects in Magnetostrictive Actuators. Proc. 9th International Conference on New Actuators, p.367-370.

Kuhnen, K., Schommer, M., Janocha, H., 2007. Integral feedback control of a self-sensing magnetostrictive actuator. *Journal of Smart Materials and Structures*, **16**(4):1098-1108. [doi:10.1088/0964-1726/16/4/019]

Pratt, J., Flatau, A.B., 1993. Development and analysis of a self-sensing magnetostrictive actuator design. *Proceedings of SPIE*, **1917**:952-961. [doi:10.1117/12.152827]

Restorff, J.B., Savage, H.T., Clark, A.E., 1990, Preisach modeling of hysteresis in Terfenol. *J. Appl. Phys.*, **67**(9): 5016-5018.

Tang, Z.F., Lv, F.Z., Xiang, Z.Q., 2007. Hysteresis model of magnetostrictive actuators and its numerical realization. *Journal of Zhejiang University SCIENCE A*, **8**(7):1059-1064. [doi:10.1631/jzus.2007.A1059]