Zero-power Magnetic Levitation by Magnetic Force Control Device using Lamination of Magnetostrictive Material and Piezoelectric Material

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ABSTRUCT

This paper describes a zero-power magnetic levitation using magnetostrictive (GMM)/piezoelectric (PZT) laminate devices. This magnetic force control is based on the inverse magnetostrictive effect of magnetostrictive material, whereby the magnetization of the GMM hence a magnetic force is control by the applied voltage to the PZT. Because the PZT is considered electrically capacitive in steady state, no electric energy is required to maintain constant magnetic force. We propose a magnetic levitation using a magnetic force control device with laminate composites of the GMM and PZT. Zero-power consumption of the levitation system in keeping a constant gap was confirmed by the measurement of the input current to the PZT.

INTRODUCTION

Generally, a magnetic force is produced and controlled by electromagnets. As a result of improvements in magnetic materials, most of the electrical energy input to the electromagnets is converted to mechanical energy, but part of it is inevitably dissipated as Joule loss in the coils due to their resistance. In controlling magnetic forces during long periods of operation, Joule loss can represent a significant loss of energy. Magnetic levitation systems using electromagnets are a typical example, since they require a continuous supply of electrical energy, most of which is dissipated as Joule heat in the coils.

To overcome this problem, we have proposed a method of controlling magnetic forces that does not use any coils [1]. The method is based on the inverse magnetostrictive effect of magnetostrictive materials, in which the variation of the magnetization of magnetostrictive materials with compressive stress is converted to the variations of magnetic force. In the method, no energy is required for maintaining control of a constant force. A magnetic force control with a giant magnetostrictive material (GMM) [2] and piezoelectric material (PZT) composite [3] has great advantages of low power consumption and low heat generation in controlling the magnetic force, because the electric energy required for maintaining the magnetic force constant is almost zero due to the capacitive property of the PZT. In this paper, we propose a magnetic levitation using a laminate composite of GMM and PZTs. The device, three laminate composites integrated into magnetic circuit, is employed to perform the magnetic levitation such that the magnetic force acting on a levitated yoke is counterbalanced with gravity. The input current to the PZTs during the levitation was measured to demonstrate the advantages of low power consumption. The step response of the levitation was also improved by adjusting the gain of the PID controller.

Magnetic force control with laminate composite of magnetostrictive/piezoelectric material

The magnetic force control is based on the energy conversion of electric energy and magnetic energy of a laminate composite of giant magnetostrictive material (GMM) and piezoelectric material (PZT). The composite is a GMM which both sides are bonded with PZTs (Fig.1 (left)). The GMM has a magnetically easy axis in the x-direction where its magnetization largely changes with applied mechanical stress by the inverse magnetostrictive effect and is used as ground electrode. The PZTs are polarized in the z-direction (the top and bottom surface are positive electrodes) and shrinks in the x-direction with applied voltage due to d31 effect. Thus, the GMM is shrunken, which magnetization is decreased when voltage is applied to the PZTs. The magnetic force control device consists of layer of three composites, a permanent magnet and magnetic yokes as depicted in Fig.1 (right). All PZTs are connected parallel and same voltage is applied to the PZTs. Ditch is made on the neighboring yokes to prevent short-circuit between the PZTs and yokes (GND).

As shown in Fig.2 (left), the device acts a magnetic (attractive) force on a movable yoke via flux in the gap. A parallel magnetic circuit are constructed; the path labeled 1 consisting of the magnet and the gap and that labeled 2 consisting of the magnet and the GMMs. Under fixed gap, the sum of the fluxes in both paths is preserved, hence the flux distribution is changed as Fig.2 (right) when the voltage applied. The decrease in the flux of path 2 caused by the shrink of the PZTs results in the increase in the flux of the path 1 and the magnetic force. That is, the magnetic force can be controlled by the voltage on the PZTs.

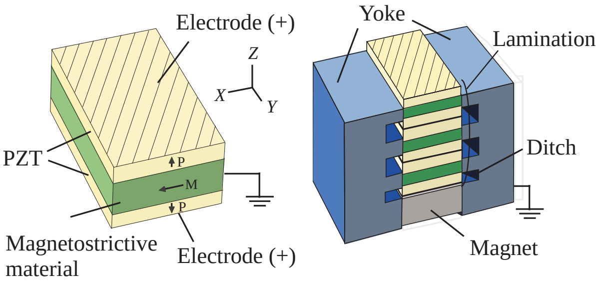

FIGURE 1: Laminate composite (left) and magnetic force control device (right).

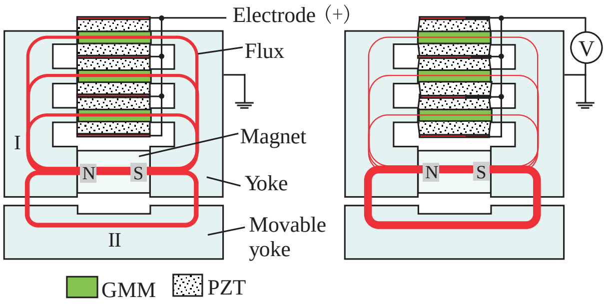

FIGURE 2: Flux distribution (left) and its variation with voltage applied (right).

Magnetic force measurement

Composites were fabricated by bonding Tb-Dy-Fe alloy as GMM of 8mm wide, 6mm long (easy axis) and 1mm thick and PZTs of 8mm wide, 6mm long and 1mm thick with epoxy resin. A permanent magnet (Nd-B-Fe magnet) of 8mm wide, 6mm long (polarization) and 3mm thick and yokes (area of 8mm by 6mm) were used. Figure 3 shows an experimental apparatus used to measure attractive force exerted on the movable yoke. Figure 4 shows the magnetic force with alternating voltage of amplitude of 0.75kV and 1.5kV and frequency of 0.2Hz with fixed gap of 0.2mm. It is observed that non-zero bias force of 1.4N occurs with zero voltage due to low permeability of GMMs and increases largely with the variation of 0.54N. The hysteresis is attributed to both hysteretic properties of PZT and GMM. Figure 5 shows the relation between the gap and magnetic force under constant voltages. The magnetic force increases with the decrease of the gap. The magnetic force also shifts higher with applying higher voltage by the reduction of the permeability of the GMMs.

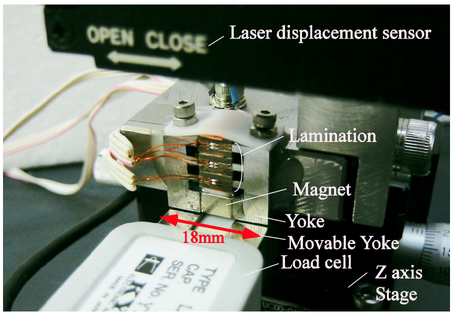

FIGURE 3: Device and experimental apparatus for measurement of magnetic force

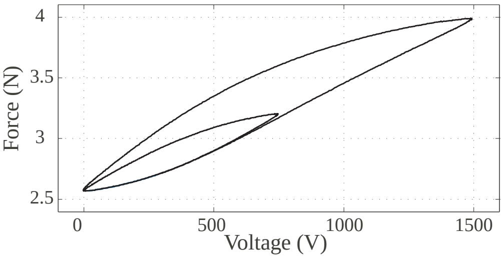

FIGURE 4: Magnetic force vs. voltage (gap 0.2mm)

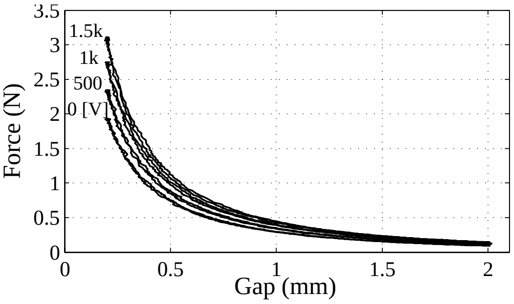

FIGURE 5: Magnetic force vs. gap (voltage fixed)

Zero power magnetic levitation

Generally, the Joule loss in the coils of electromagnets represents most of the energy loss in maintaining control of constant magnetic force. Magnetic levitation using electromagnets is typical example, which continuously consumes power to maintain the levitation. To minimize the loss, electromagnets with permanent magnets which provide bias forces are alternatively employed. However its low-power consumption is only valid at a certain gap where bias force acting on a levitated object is equal to its gravity. The magnetic levitation by use of the device has the same advantage but is superior to the conventional one using electromagnets because it does not require any power in any steady state. We performed magnetic levitation using the device and investigated this advantage.

The configuration of a magnetic levitation system is depicted in Fig.6. The magnetic force acting on a levitated yoke affixed on a linear guide (mass m=150g) was controlled so as to achieve the levitation; the force is counterbalanced with the gravity. The control voltage (maximum 1500V) fed to the PZTs was calculated by a DSP using sensed signal of the gap with a laser displacement sensor (resolution: 1μm and response frequency: 300Hz). The input current to the PZTs was measured by a current prove (resolution 1V/A).

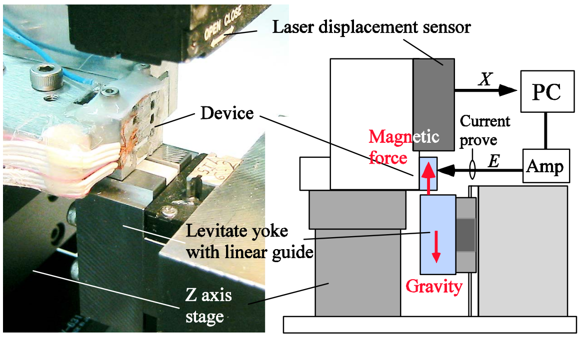

FIGURE 6: Experiment apparatus for magnetic levitation

The magnetic force F is a function of gap X and voltage E. Assuming that the bias force F_0 is equal to the gravity at operation point P_0 (X_0, E_0), F at small deflection (x, e) from P_0 is given as

$$F = F_0 + dF = F_0 + K_X x + K_E e \qquad (1)$$

$$K_X = \left.\frac{\partial F}{\partial x}\right|_{E_0, X_0}, K_E = \left.\frac{\partial F}{\partial e}\right|_{E_0, X_0}$$

Because F_0= mg, the kinetic equation of the yoke is given as

$$m\ddot{x} + K_X x + K_E e = 0 \qquad (2)$$

This system is unstable because K_X in Eq.(2) is negative. By applying PD control such that input e is a linear combination of x and $\dot{x}$:

$$e = K_p x + K_d \dot{x} \quad \left(K_p, K_d > 0\right) \qquad (3)$$

Substitution of Eq.(3) into Eq.(2) gives

$$m\ddot{x} + K_d K_E \dot{x} + \left(K_X + K_p K_E\right) x = 0 \qquad (4)$$

This system is stable if

$$K_X + K_p K_E > 0 \qquad (5)$$

K_p to satisfy Eq.(5) around X_0=0.25mm was determined by K_X and K_E measured from the experimental results of Figs.4 and 5. The force controlled around P_0 where K_p is set to 10k, 30k, 50k and 80kV/mm is plotted in Fig.7. The inclination of the curve changes from negative to positive when K_p > 30kV/mm.

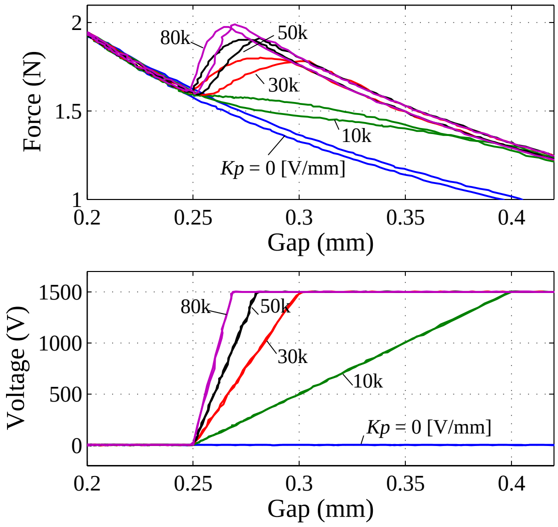

FIGURE 7: Relation between gap and magnetic force (top) and control voltage (bottom)

Experimental results

With X_0=0.25mm, K_p=50kV/mm and K_d=0, the yoke was levitated maintaining the gap of 0.25mm. We then applied disturbance by flicking the stage. Figure 8 shows the response of the gap, voltage and current with the disturbance. The vibration was successfully suppressed by control of the voltage on PZTs. Even K_d =0, air, friction of the linear guide and the hysteresis of the magnetic force were acting as damping. Notice that the current remains almost zero in the steady state. (deflection of 1mA is noise of the measurement) This is due to the capacitive property of the PZTs. The leakage current of the PZTs is considered very small (less than noise). Furthermore, as shown in Fig.9, the current vs. voltage in the vibration is almost same as that by capacitance i.e. the voltage delays about 90 degree to the current. That is, the PZT is considered almost capacitance when the frequency of the vibration is low enough to the natural frequency of the composite (130kHz). Therefore, the power consumption by the PZTs in the suppression of the vibration is also small, only the dielectric loss and work conducted on the yoke.

Figure 10 shows the comparison of the step response with parameter of K_p when X_0 was changed from 0.27mm to 0.24mm. Generally the bandwidth increases with K_p. But the response of K_p = 80kV/mm obtained here was not good because the effect of the damping became relatively small. In addition, the voltage saturated, indicating the frequency response of this system is limited by the output rate of the power amplifier. We added integral controller to reduce the deviation. Figure 11 shows the comparison of the step response with parameter of the integral gain K_i when X_0 was changed from 0.29mm to 0.27mm. The deviation in the steady state became zero with K_i. Finally we could achieve minute step motion of 1 μm which is almost the same resolution as that of the displacement sensor.

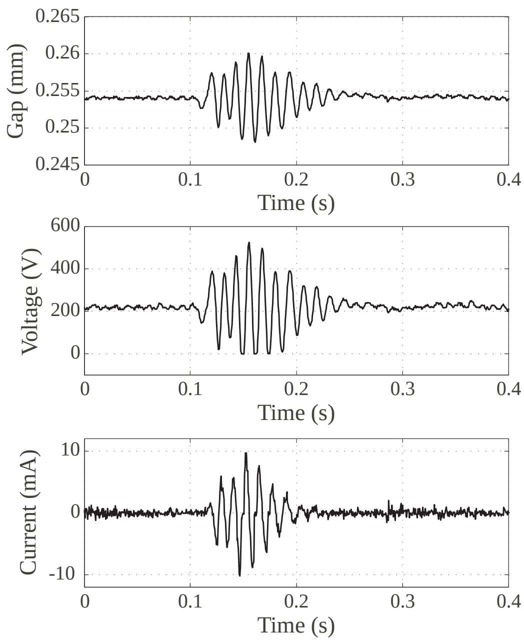

FIGURE 8: Time response when disturbance applied (top: gap, middle: voltage, bottom: current)

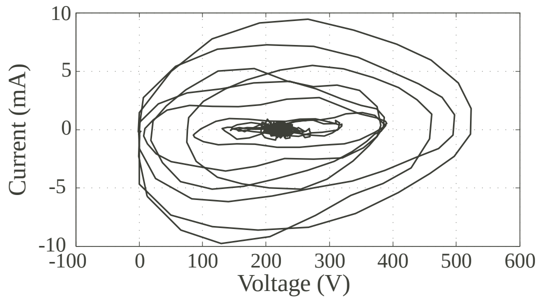

FIGURE 9: Current vs. voltage

CONCLUSION

We proposed a zero-power magnetic levitation using a magnetic force control device with laminate composite of GMM and PZTs. By controlling the voltage of the PZTs, we could achieve the lavation of the ferromagnetic yoke and confirmed the low power consumption. Future work must be addressed on the improvement of the device. For practical application, we hopefully enlarge the variation of the magnetic force by modification of the magnetic circuit and reduce the operating voltage.

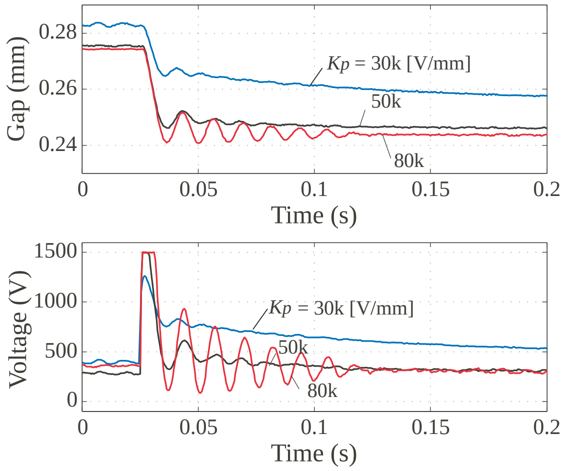

FIGURE 10: Comparison of step response with parameter of K_p (top: gap, bottom: voltage)

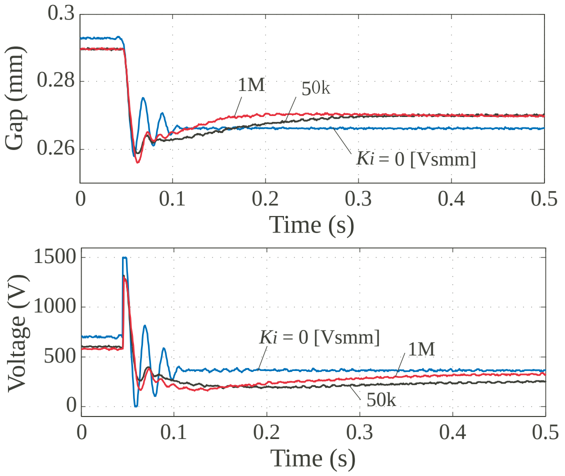

FIGURE 11: Comparison of step response with parameter of K_i (top: gap, bottom: voltage)

Reference

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[2] G.Engdahl, Handbook of giant magnetostrictive materials, Academic Press, 2000.

[3] T.Ueno *et al.*, New magnetic force control device with composite of giant magnetostrictive and piezoelectric materials, *IEEE* Transactions on Magnetics, 39, pp.3534-3540, 2003.