Combination of Magnetostrictive/ Piezoelectric Materials Composite and Electromagnet for Zero Power Levitation *

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***Abstract* – This paper presents zero-power levitation using a composite of magnetostrictive (GMM) /piezoelectric (PZT) materials. The control of the magnetic force is based on the inverse magnetostrictive effect of the GMM, by which the magnetic force can be varied with applied voltage on the PZT. The distinctive advantage of the composite is zero power consumption while maintaining a constant magnetic force due to the capacitive property of the PZT. So far we have succeeded the magnetic levitation and verified the advantage of zero power in stationary state. The robustness is, however, low due to the limited variation of the magnetic force. In this paper, we propose the combination of the composite and electromagnet, where the bias gap is adjusted by the composite and the motion of the levitated yoke is stabilized by the electromagnet. The experimental results of step response verified the zero power consumption in both devices and that the composite driven by small DC-DC converter functions sufficiently to adjust the bias gap.**

***Index Terms* – Composite, magnetostrictive material, piezoelectric material, zero-power, bias gap control.**

I. Introduction

Magnetostrictive material provides new idea of magnetic force control using mechanical force [1]. This method is based on the inverse magnetostrictive effect, by which compressive stress applied to the magnetostrictive material is converted to the variation of the magnetic force via magnetic circuit. Due to the stress-based control, this method features no energy consumption to maintain constant of the magnetic force. For instance, placing weight on the material can keep the change of the force with no energy dissipation because the variation of the force is attributed on elastic (potential) energy converted to the magnetic energy.

Innovative devices to control magnetic force are created from the composite of the magnetostrictive material with other functional materials. Especially, composite of magnetostrictive and piezoelectric materials provides magnetic actuator with distinctive features [2][3]. The piezoelectric material can sufficiently change the stress on the magnetostrictive material with voltage applied, and its electric energy required to maintain the constant of the force is zero due to the capacitive property of the piezoelectric material i.e. once it is charged, the current flowing to the material becomes zero even with the voltage applied. This characteristic is advantageous in the applications such as linear step motor or magnetic suspension for positioning which maintain the constant of the magnetic force in most time of the operation.

So far, we have demonstrated sufficient capability of controlling magnetic force in a composite of a giant magnetostrictive material (GMM) [4][5] and stack PZT actuator. The magnetic, mechanical and magnetostrictive properties of the GMM, low permeability, low Young's modulus and high piezomagnetic coefficient, are the most utilized in the composite with stack PZT with high force and high stiffness. The composite of simple configuration, both materials bonded to iron yokes for magnetic circuit, is reported to vary the magnetic force of the order of N more than 50 % from the bias force [6]. For the applications, we have investigated the potential of composite for magnetic levitation and verified its zero power characteristics [7]. Even though the levitation was achieved, its robustness is, however, low due to the limitation of the variation of the magnetic force. Our strategy is combination of the composite and electromagnet for zero power, where the bias force is adjusted by the composite and the motion of the levitated yoke is stabilized by the electromagnet. Therefore the system realizes zero power in controllable bias gap with high robustness. In this paper, we describe the principle of the composite and levitation system and investigated the characteristics. Measurement results of step response verified the zero power consumption in both devices and that the composite driven by small DC-DC converter functions sufficiently to adjust the bias gap.

II. Composite

Figure 1 shows the magnetic force control device, which is a combination of the composite and a magnetic circuit. The purpose of the composite is to control the magnetization of a giant magnetostrictive material (GMM, Tb-Dy-Fe alloy), grain oriented in the longitudinal

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direction, by two stack PZT actuators via mechanical stress. Therefore, the GMM and two PZTs with same length are lined up and the both ends are glued to iron yokes which are stiff enough to prevent the deformation by bending. When the voltage is applied, the GMM is strained in the longitudinal direction with the extension of the PZTs and its magnetization is increased due to the inverse magnetostrictive effect. In addition, the yokes are loaded compressive force by tightening nonmagnetic bolts via Belleville springs to add pre-stress on both materials. The exerted pre-stress allows both the materials to be used under compressive load and it induces the decrease of bias of the magnetization of the GMM.

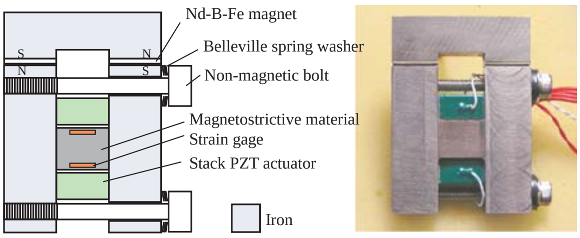

Fig. 1 Configuration of composite

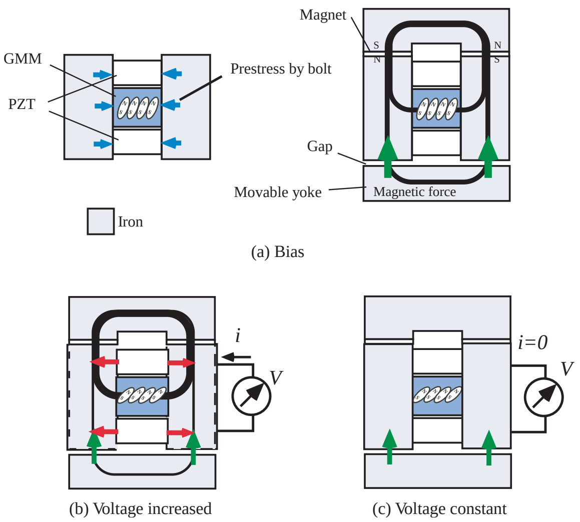

Fig. 2 Principle of magnetic force control and zero power consumption (voltage zero of bias (a), voltage increased (b) and voltage constant (c)

The magnetic force control device is the composite in conjunction with permanent magnets with a back yoke attached. Figure 2 (a) illustrates the flux path in the device with a movable iron yoke beneath. The magnet makes two parallel magnetic circuits; one consisting of the magnet and the gap which contributes on the magnetic (attractive) force on the movable yoke, and the other consisting of the magnet and the GMM. The magnetization of the GMM is suppressed in advance with the compression of the bolts as shown in left of Fig. 2 (a), by which the bias of the force is adequate. The operation of the device is simply explained as follows. When the voltage is increased with fixed gap, the flux distribution is changed as shown in Fig. 2 (b). The extension of the PZTs reduces the compressive stress on the GMM, whereby the magnetization is increased. Since the total of the fluxes is approximately conserved for a fixed gap, the increase of the flux in the GMM results in the decrease of the flux in the gap and resulting magnetic force. Thus, the variation of magnetic force from bias can be controlled by the voltage on the PZTs. The most advantage of the composite is zero power consumption in static operation. The electric energy required to maintain the constant of the force becomes zero due to the capacitive property of the PZT as shown in Fig. 2 (c). Once the PZTs are charged to change the force, the current becomes zero even with the voltage applied.

III. Levitation by Zero Power

A. *System configuration*

Figure 3 shows the experimental setup for levitation. The composite and an electromagnet aligned exert magnetic forces on levitated yoke affixed on a linear slider (total weight: 300 g). The aim of the combination is to adjust the bias force or bias gap with the composite and stabilize the motion of the yoke by the electromagnet. The GMM (Terfenol-D) and stack PZT actuators (AE050508, NEC TOKIN Co. Ltd, Japan) for the composite are 8×8×10 mm^3 and 5×5×10 mm^3 respectively, which were bonded by epoxy resin to iron yoke (SS400) with a gap area of 10×8 mm^2. After the adhesion in room temperature, a uniform pre-stress was added on the GMM by tightening two stainless bolts. The dimension of the Nd-B-Fe magnet in conjunction with the back yokes is 10×5×1 mm^3. The electromagnet is iron yoke (gap area of 10×8 mm^2) with coil of 200 turn wound with permanent magnet of 10×8×1 mm^3. Gap sensor (EX-008, resolution: 0.3 μm, response 0.1 ms) was placed between both devices.

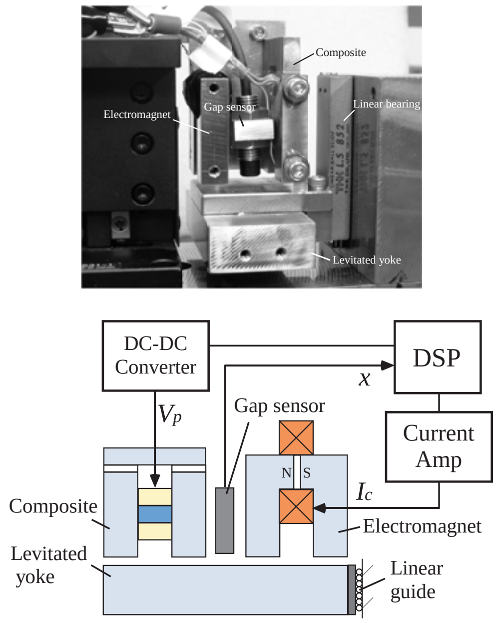

Fig. 3 Experiment setup

The relationship between the gap and magnetic force measured by a load cell is depicted in Fig. 4. The voltage V_p applied on the PZTs and current I_c to the coil are parameters. The magnetic force contributed by two devices including the permanent magnet is increased with the decrease of the gap. It is observed that the magnetic force varied with I_c is shifted lower with the increase of V_p. Figure 5 shows the magnification around the gap of 0.5 mm, force of 3 N, and I_c of 0 A. The area between the curves of 0 and 200 V is regarded the range where zero power consumption is valid in both devices. For example, mass for the levitation is fixed; the line with arrows 1 indicates controllable bias gap, while the bias gap can be maintained constant even if the mass is changed within the line with arrows 2.

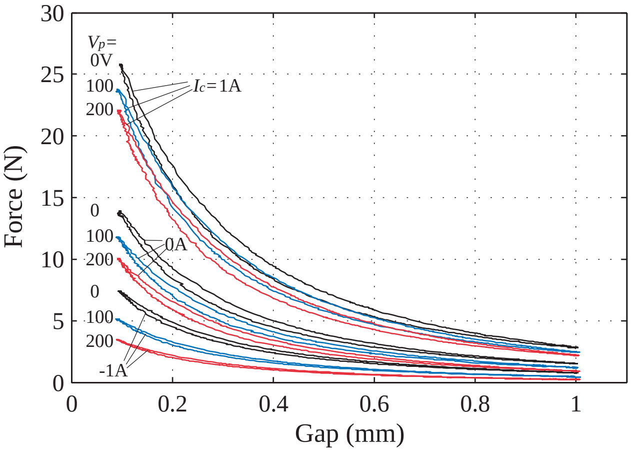

Fig. 4 Magnetic force vs. gap with parameters of the current I_c to coil and voltage V_p on PZTs.

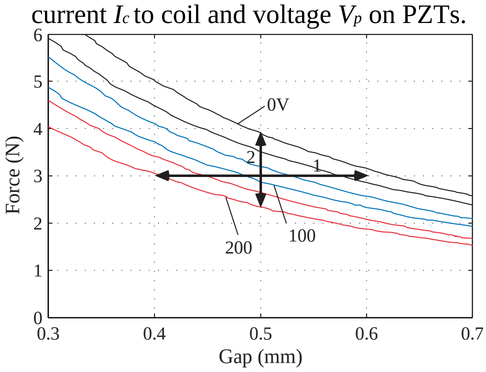

Fig. 5 Magnification of the force around gap of 0.5 mm, force of 3 N and I_c of 0 A.

B. *Levitation experiment*

The levitation experiment was conducted. The control voltages calculated by DSP (sampling rate 0.1ms, DSPACE, Co. Ltd) from the detected gap sensor were fed to the PZTs and electromagnet through a DC-DC converter (BYH05-200S01, Belnix Co. Ltd) and current amplifier (BPS120-5, Takasago Ltd) respectively. The converter features small size providing maximum voltage of 200 V (control input of 3 V) and output current of 1mA, which can be energized by dry cells of 4.5 V. The input current fed to the composite was measured by a current probe (AM503, resolution 1 V/A, Tektronics, Co. Ltd) and applied output voltage was by a high voltage probe. We tried to control the bias gap with fixed mass of the levitation, thus, the control outputs for the electromagnet (1) and campsite (2) were calculated by following equations.

$$I_c = k_{pc}x + k_{dc}\dot{x} + k_{ic}\int I_c dt \qquad (1)$$

$$V_p = k_{pp}x + k_{ip}\int xdt \qquad (2)$$

where x is the deviation from the set point of the bias gap X, and k_p, k_i, k_d with subscript of c (coil) or p (PZT) are gains for PID controller. We first achieved the levitation only by the control of the electromagnet then started the integral control by the composite. Figure 6 shows the result of step response when the voltage V_p was changed from 0 to 200 V. The gains were set k_{pc} = 15 A/mm, k_{dc} = 0, k_{ic} = 5.0 A /s and k_{pp} = 2000 V/mm. The gap was successfully varied between 0.53 mm and 0.4 mm, which exhibits the controllable range of the set point X. The current to the PZTs in stationary state was observed zero due to the capacitive property. The delay of rising and setting time in the response is due to the limitation of the maximum current of the converter. Figure 7 shows the step response when X was changed from 0.5 to 0.47 to 0.44 mm with integral control of the composite (k_{pi} = 1000 V/s). The converter could control X without significant influence on the stability of the levitated yoke. Figure 8 shows the response when V_p was changed between 0 to 200 V with triangle wave. The behaviour of the gap was influenced by the performance of the converter and hysteresis of the magnetic force inherited from the characteristics of the piezoelectric materials.

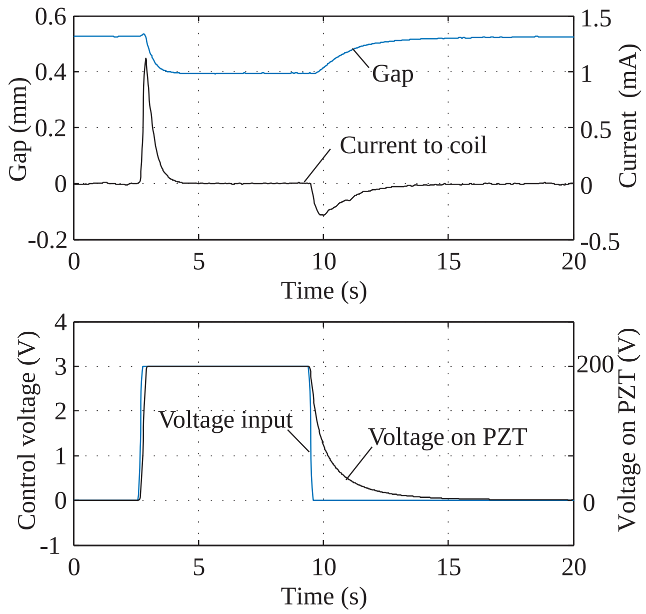

Fig. 6 Step response of gap and input current to PZTs (top), and control and output voltages for PZTs (bottom) when V_p was changed from 0 to 200 V.

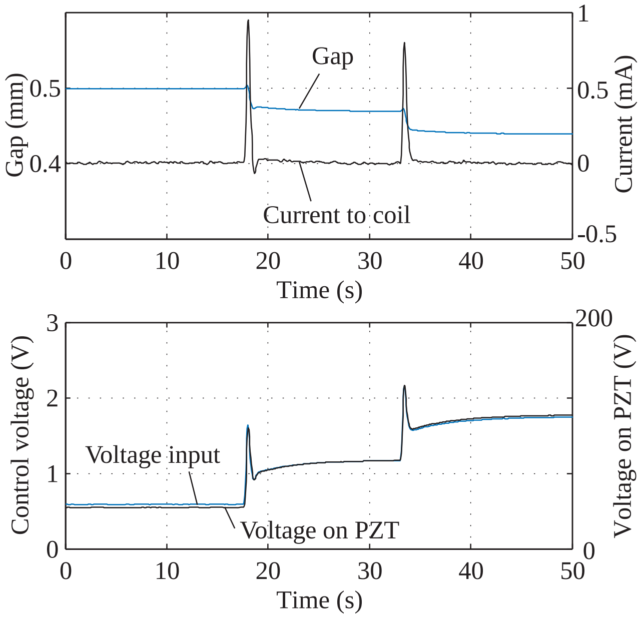

Fig. 7 Step response of gap and input current to PZTs (top), and control and output voltages for PZTs (bottom) when X was changed from 0.5, 0.47 to 0.44 mm.

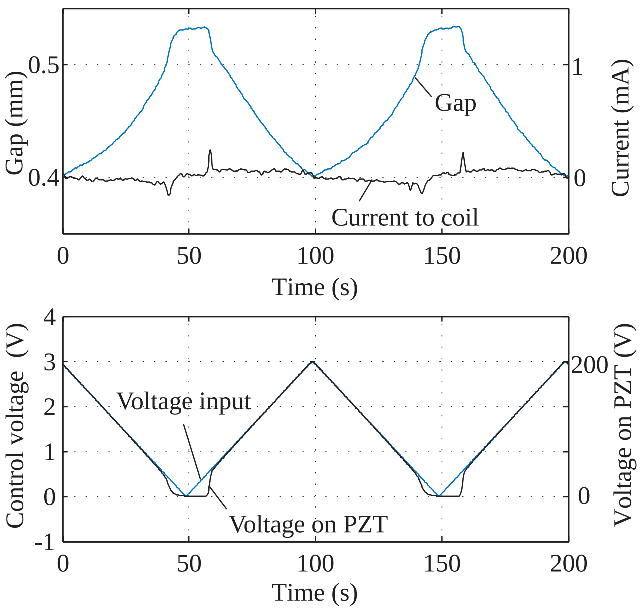

Fig. 8 Responses of gap and input current to PZTs (top), and control and output voltage for PZTs (bottom) when V_p was changed between 0 to 200 V with triangle wave.

IV. Conclusion

The magnetic levitation using the combination of a composite of magnetostrictive/piezoelectric materials and electromagnet was investigated. The bias gap was successfully controlled with applied voltage to the PZTs and maintained zero power consumption in static state. The technique of the combination is suitable for high precision positioner or stage where the power consumption and temperature rise should be avoided. Other applications can be considered, for example, convey system where the constant gap should be maintained with the variation of the pay load. The levitation results using DC-DC converter with small size demonstrates the possibly of compact system in power supply, which will literally realize the zero power characteristics.

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